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THE ISSUE OF THE COMPRESSIVE STRENGTH OF FINE-GRAINED REINFORCED CONCRETE

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Keywords: concrete, high-quality, charts, model
Abstract: To obtain high-quality concrete constructions it is not enough to execute it only in concrete of high class. One of the effective ways to improve the reliability and durability of concrete is its reinforcing by various kinds of fibers. The article presents the researching results of the influence of brands of portland cement and disperse reinforcing by polyethylene terephthalate fibers (PET-fiber) on concrete durability. Standard compression tests of the cubical prototypes of fine-grained sand concrete made of two brands of portland cement – PC400 and PC500 with different percentage of PET-fibers have been conducted. The optimum content of PET-fibe, wherein there is a maximum increase of durability of fine-grained fiber-reinforced concrete, has been set.

1 Theories of the concrete strength

There are three groups of theories of the concrete strength: phenomenological, statistical and structural [1].

Phenomenological theories describe the concrete as a homogeneous isotropic elastic body [2]. Special attention is given to the dependence of the strength on external loads. The laws, by which we can judge about the beginning of the material destruction under the complex stress, about the behavior of material under the simple tension, compression or bending, are set. However, the phenomenological strength theories cannot explain the internal processes in the concrete (deformations of contraction and swelling, ectothermy, etc.).

According to the statistical theories, the existence of continuous isotropic environment and separated air voids and microcracks in concrete is presumed. These theories determine the reasons of the huge differences between the actual strength and the results of theoretical calculations. It is usually determined by the defect structure, although without consideration of the structure. Nevertheless, statistical theories cannot explain the influence of many processing factors not leading to the formation of cracks but significantly changing the stressed state of the material on concrete strength.

The most promising for the technological problems of designing concrete structures is the usage of the structural strength theories based on certain models of the concrete structure [4]. A common feature of all the structural theories is the consideration of the concrete as a polystructural material in which, depending on the nature and mechanism of structure processes, the distinction is drawn between:

- microstructure (the structure of the cement matrix);
- mesostructure. (the structure of the solution in concrete, considered as a two-component system «aggregate – cement stone»);
- macrostructure (the structure of two-component systems «pore space – solution»).

The given division of concrete structure is explained by the fact that the mechanism of formation and properties of macro-, meso- and microstructure are fundamentally different. Each level of structure can be characterized by certain physical parameters defining its peculiar properties. So, the most important technological factors which influence the formation of the cement stone microstructure are the cement brand, its chemical and mineralogical composition, fineness of grinding, water-cement ratio and the conditions of hardening.

2 High-quality concrete producing

As a cementing material for high-quality concrete producing it is recommended to use Portland cement with the brand not lower than 400 and the qualitative characteristics meeting the requirements of GOST 31108-2003 [5]. The usage of cement below the recommended brand leads to its significant overrun. In turn, the increased cement stone content in concrete, which has such negative properties as creep, reduced crack resistance, high shrinkage deformations, causes a decrease in physical-mechanical and operational properties of concrete.

Polystructural character of concrete affects the work of the structures under load. The behavior of concrete is different at different levels of loading. At low load levels processes associated with the redistribution of effort due to technological factors and stress concentration from external influences prevail. These processes lead to the transition of technological microdefects in operating ones. The behavior of concrete at medium levels of loading is characterized by the interaction and development of defects and by combining of them. At loads close to the destructive, the main role is played by the redistribution of forces in the construction and transformation of microcracks into main macrocracks.

Therefore, the execution of the construction only made of high-class concrete will not ensure its fail-safe running as a whole. To improve the resistibility of the artificial stone to compressive, tensile and transverse (bending) stresses, it is recommended to use disperse reinforcing. Disperse reinforcing is a steady distribution of elastic, short (5-20 m) and thin (10-100 micrometer diameter) fibers that can be made of glass, metal, basalt or polymer throughout the volume. The concrete and reinforcing due to the high adhesion ensure the solidity of the construction and its performance as a single integrated material – reinforced concrete.

In the reinforced concrete production it is necessary to set the range of the volume content of fibers ‘μ’ within which brittle fracture is excluded [6]. However, in the range μmin – μmax another characteristic point is of great importance. It corresponds to the moment of fiber cement frame creation ‘μk’, before and after which the behavior of the composite and its properties differ significantly (Figure 1).

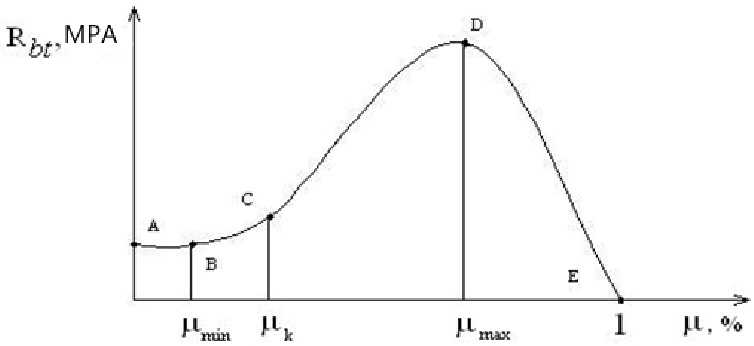

Figure 1 The character of strength changing of reinforced concrete depending on the volume concentration of fibers

The AB phase is characterized by small saturation when the fibers are removed from each other on a considerable distance («zone of diffused reinforcing»). The strength of reinforced concrete is characterized by the strength of the matrix and does not differ from it. The BC phase is «the area of concentrated reinforcing». When the matrix cracks, fibers are able to take the load and ensure the bearing strength of reinforced concrete. Point C is the moment of merging of the contact areas of fiber – matrix and creation of fiber-cement framework. Further and more intensive increase of strength of reinforced concrete takes place on the CD phase. It is the result of compaction of the cement stone between the fibers. Point D corresponds to a maximum strength of reinforced concrete. The DE phase is characterized by the strength reduction due to the thickness reduction of the matrix layer so the material shows a tendency to segregation even at low loads.

Experimental researches have been done to determine the optimal volume content of fibers ‘μ’ for fine-grained reinforced concrete. The composition of fine-grained sand concrete with a compressive strength of B5 was designed previously. It was used in the creation of 7 series of experimental cubic prototypes, made of reinforced concrete of two portland cement brands – PC400 and PC500, with various percentage content of polyethylene terephthalate fibers relative to the total fiber mass from 0 to 0,9 %. The ultimate saturation of reinforced concrete by similar types of fiber is 0,9 % [7]. When the concentration of fiber exeeds 0,9 % the widespread reduction in all strength parameters is observed. Secondary polyethylene terephthalate fibers (PET fiber) received by means of vertical blowing and produced by "PET" LTD Tchaikovsky was used for concrete reinforcing. The diameter of the fibers is 10-20 microns, length is up to 20 mm. The prototypes were tested on the axial compression to the limit state in accordance with GOST 10180-90.

According to the results of experiments the functional dependence of the strength of reinforced concrete under axial compression from percentage of reinforcing by PET fiber and brand of portland cement was built. The obtained diagrams are presented in figure 2.

Compared to the chart (Figure 1) the behavior of the material to the point ‘μk’ is multiple-valued. Obviously there is an influence of some technological factors that require additional researches. The zones of increasing of strength of reinforced concrete are practically the same, although their locations are slightly different: μmax ≈ 0,7 % (PC400); μmax ≈ 0,55 % (PC500).

3 Mathematical model and factors of concrete structure formation

As a cementing material for high-quality concrete producing it is recommended to use Portland c

The plotting of a mathematical model of the standards for evaluation of different physico-mechanical and performance properties of reinforced concrete based on the influence of several factors allows to judge the progress of the process of structure formation more accurately. The more factors are considered, the more accurate the model is. The results of the experiments allowed us to build the model of evaluation standard of the strength of reinforced concrete. According to this model, the chart depending on the concentration of PET fibers is ploted (Figure 3):

$$P = P(x) \quad (1)$$

$$P_1 = 6307 + 93366 \cdot x - 417604 \cdot x^2 - 227204 \cdot x^3 + 3206947 \cdot x^4 - 4495654 \cdot x^5 + 1827215 \cdot x^6; \quad (2)$$

$$P_2 = 18067 + 305367 \cdot x - 4058509 \cdot x^2 + 18392384 \cdot x^3 - 37018022 \cdot x^4 + 34498333 \cdot x^5 - 12199867 \cdot x^6, \quad (3)$$

where:
P1, P2 – the values of the strength (failure loads) for PC400 and PC500 respectively (kg/cm2), x – the fiber content (%).

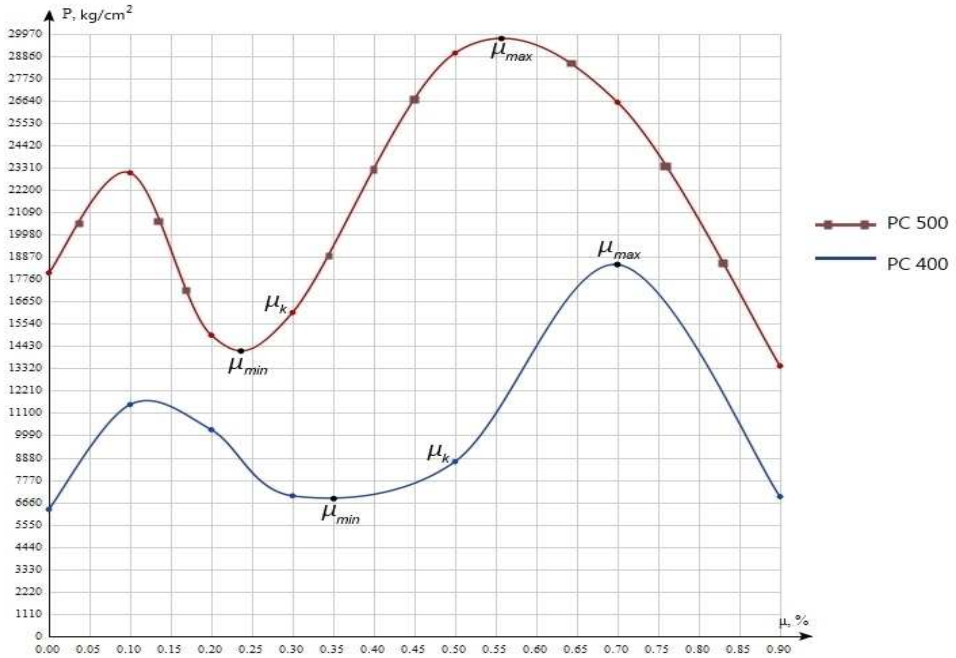

Figure 2 The dependence of the strength of reinforced concrete under axial compression from the reinforcing ratio of PET fiber and brand of portlandcement

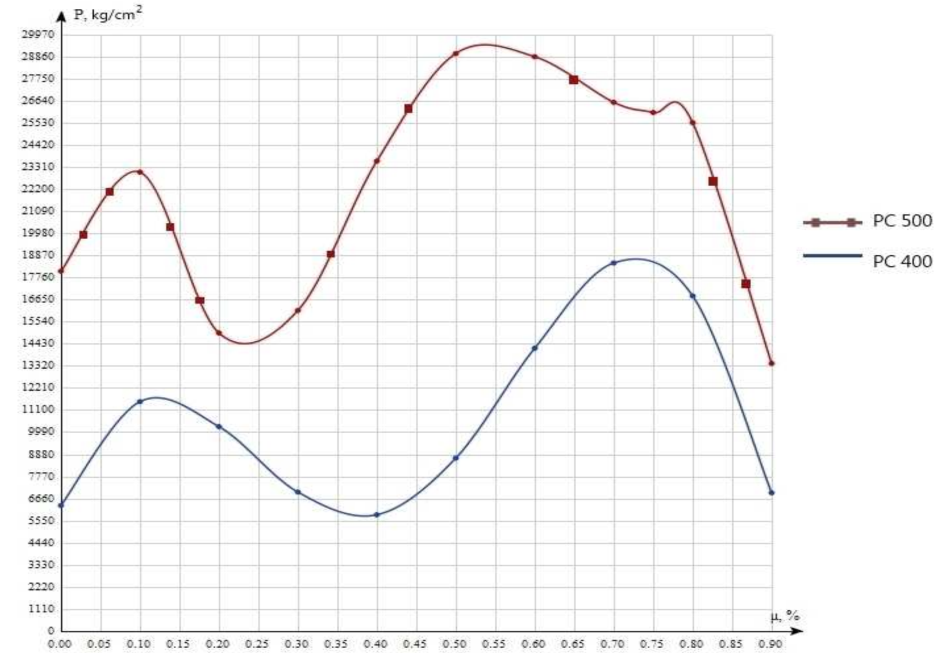

Figure 3 Chart prediction of bearing capacity of fine-grained reinforced concrete

To determine the effect of brand of portland cement on strength of fine-grained reinforced concrete the values of the strength chart were compared (Figure 4). Here a÷g is a difference in strength of reinforced concrete samples on the basis of PC400 and PC500.

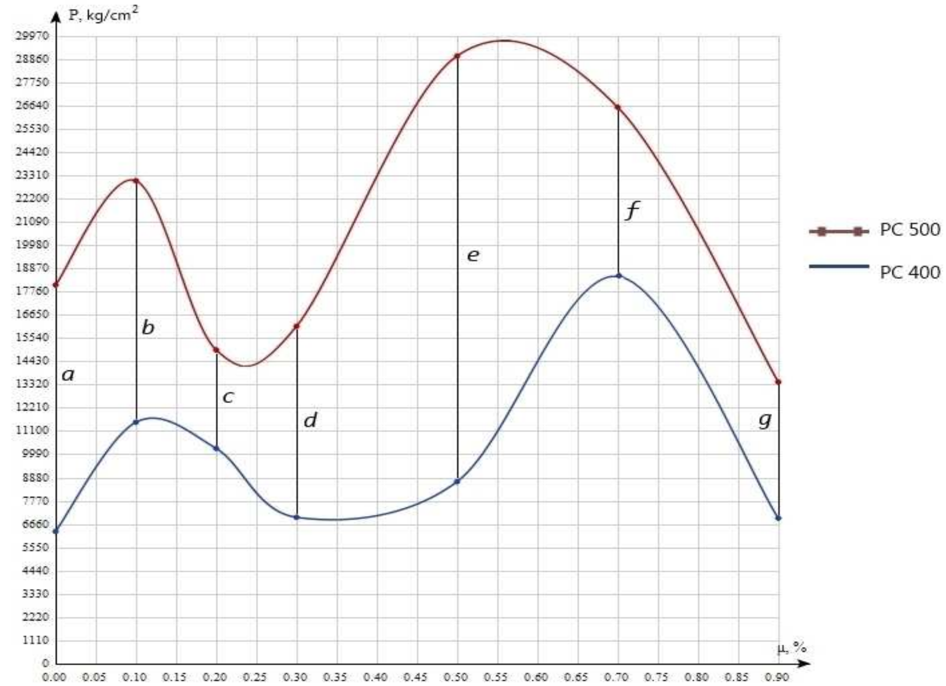

Figure 4 The interdependence of the strength of reinforced concrete based on different brands of portland cement

Having compared the values of the strength of reinforced concrete based on different brands of portland cement with different concentration of the same PET fiber, we built the function curve of the effect of type of cement and its graph (Figure 5):

$$Y_{изм} = a + b \cdot x + c \cdot x^2 + d \cdot x^3 + e \cdot x^4 + f \cdot x^5 + g \cdot x^6 \ ; \quad (4)$$

$$Y_{изм} = 11760 + 11524 \cdot x + 4701 \cdot x^2 + 9115 \cdot x^3 + 20311 \cdot x^4 + 8068 \cdot x^5 + 6498 \cdot x^6 . \quad (5)$$

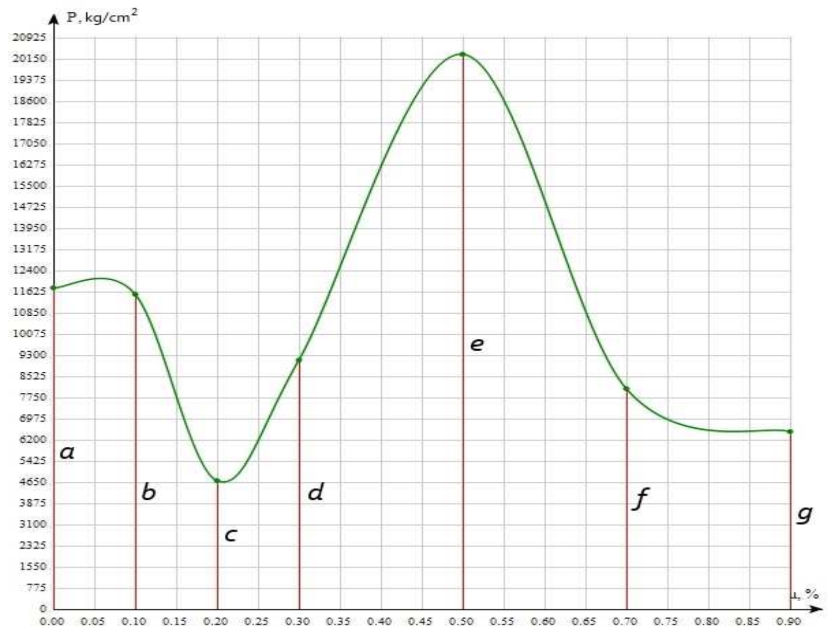

Figure 4 The graph of the function curve of the effect of cement type on the strength characteristics of reinforced concrete

4 Conclusion

Thus, the model of evaluation standard of the strength of reinforced concrete constructions is:

$$\left.\begin{aligned} P_1 &= 6307 + 93366\cdot x - 417604\cdot x^2 - 227204\cdot x^3 + 3206947\cdot x^4 - 4495654\cdot x^5 + 1827215\cdot x^6 \\ P_2 &= 18067 + 305367\cdot x - 4058509\cdot x^2 + 18392384\cdot x^3 - 37018022\cdot x^4 + 34498333\cdot x^5 - 12199867\cdot x^6 \\ Y_{изм} &= 11760 + 11524\cdot x + 4701\cdot x^2 + 9115\cdot x^3 + 20311\cdot x^4 + 8068\cdot x^5 + 6498\cdot x^6 \end{aligned}\right\} \quad (6)$$

This model allows to carry out a design test and to make additional experiments on its basis to refine the mathematical model and exact laws of structure formation. Also, it can be argued that the reinforcing by polyethylene terephthalate fibers allows to reduce the probability of brittle fracture, to increase the ability to bear various loads and also to solve partly a relevant environmental problem of our time.

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EVALUATION OF QUANTITATIVE AND QUALITATIVE INDICATORS OF GROUNDWATER IN TERMS OF THEIR USABILITY AS A PRIMARY ENERGY SOURCE FOR HEAT PUMPS

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Keywords: heat pump, groundwater quality, quantity of groundwater, hydrogeological conditions
Abstract: The central aim of this article was based on knowledge of the quality and quantity of groundwater on the territory of the Slovak Republic to determine appropriate placement selected heat pumps water / water type. It was necessary to determine the technical parameters of selected devices and their requirements for quality and quantity of primary heat source, ie groundwater and hydrogeological conditions of Slovakia. As a bonus this article provides an overview of current developments in the Slovakian market for heat pumps.

1 Introduction

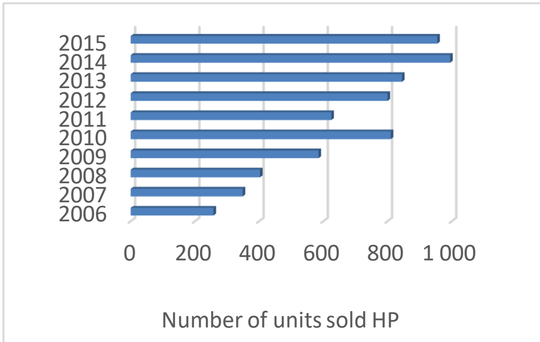
The Slovak Republic is among the countries with the richest supplies of water in its territory, whether on the surface or under the surface. Not only the geological structure of Slovakia, but also its geographical location in Central Europe, with a relatively even distribution of precipitation during the year, is of great importance. These waters have different uses, of course the main is supply drinking water for the population, further in the industry, agriculture, healthcare, and so on. As part of the European Union's effort to achieve sustainable development, the industry sector has grown strongly in recent years with a focus on renewable energy, for normal household applications. We can rank here heat pumps (hereafter HP). Regarding the efficient use of water, heat pump of water / water type is a very good example, due to its high efficiency at the optimal qualitative and quantitative conditions of the used groundwater.

The main objective of this contribution is to find out, on the basis of the analysis of indicators of quantity and quality of groundwater on the territory of the Slovak Republic, the appropriate placement of selected heat pumps from different producers. To achieve this, we chose two partial goals. Firstly to detec and compare the requirements of individual heat pumps to the primary source of thermal energy, ie groundwater, in terms of quantity and quality required for optimal operation. The second sub-objective is to identify and map groundwater status in the Slovak Republic based on qualitative and quantitative aspects.

2 Heat pumps on Slovakia

The HP market is very difficult developing, as is shown by Chart no. 1. While only about 260 units were sold in 2006, 800 were sold in 2010 and almost 1,000 units were sold in 2014, of which 585 were air / water and 312 were water / water. In 2015, the number of sold air / water units increased to 721, but only 234 pieces were sold in the land / water / water type [1][2].

Chart no. 1 Development of sales of HP in Slovakia in 2006 – 2015 (processed according to [1] [2])



In addition, from 1 December 2015 until the end of 2018 in Slovakia, the project "Green for Households", which is managed by the Ministry of Environment of the Slovak Republic through the Operational Program Quality of the Environment, is under way. Families in Slovakia can, after fulfilling the conditions set, obtain subsidies for selected facilities generating electricity or heat, which also includes HP. The aim of this project is to promote an energy efficient, low-carbon economy in all sectors and to revive the market environment with RES facilities in households [2].

3 Hydrogeological circumstances Slovakia

Slovak water management has a significant focus on groundwater, which is justified due to the fact that the total area of the Slovak State of 49 035 km2 occupies the hydrogeological area of about 43 420.4 km2 (88.5%). [3] [4] However, the amount of groundwater is unevenly distributed on the territory of Slovakia, while abundant reserves are recorded in the Bratislava and Trnava regions (46%), and in the Prešov and Nitra regions it is significantly lower. [5] Individual territories that have the same or similar groundwater regimes (hydrogeological conditions) and are defined by the geological boundary are called hydrogeological units. In Slovakia we divide them into seven [6]:

- Hydrogeological whole of the nuclear mountains, crystalline Veporské vrchy and Slovenské Rudohorie,
- Hydrogeological whole of mesozoic rocks,
- Hydrogeological whole of the cliff band,
- Hydrogeological whole of paleogeneous sediments of flysch band,
- Hydrogeological whole of sedimentary neogen,
- Hydrogeological whole of non-vulcanites,
- Hydrogeological whole of quaternary sediments.

Besides the hydrogeological units, the territory of Slovakia is also divided intothe 141 hydrogeological zonee, which serve as the basic assessment units for the water balance ofgroundwaterr. The deployment of the zones is shown in figure 1 [4]. The State Geological Institute Dionýza Štúra (ŠGÚDŠ) no longer uses this partition methodology to zones and prefers to divide into regions and units, but the Slovak Hydrometeorological Institute (SHMÚ) still applying it in its reports and water management balances.

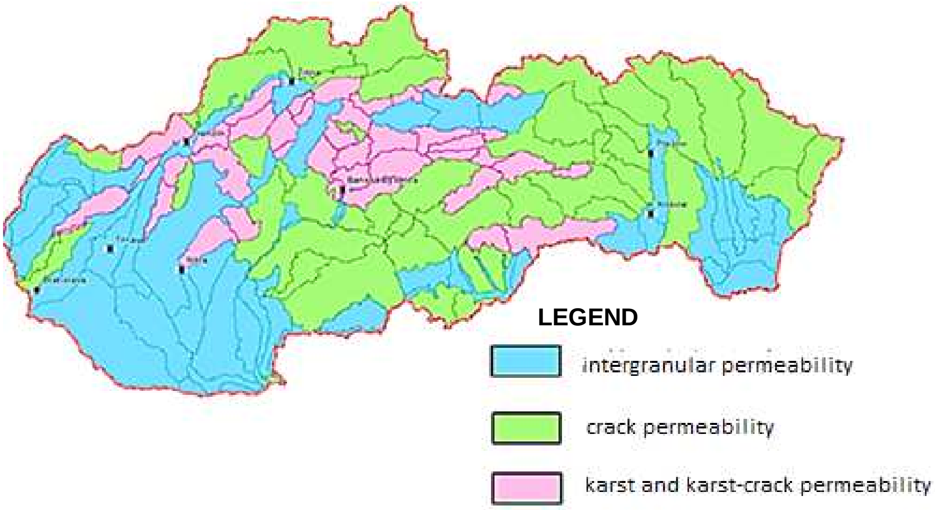


Figure 1 Hydrogeological zones in the Slovak Republic and their permeability (processed according to [4], [7])

4 The technological parameters of selected water / water heat pumps, focusing on their requirements for the quality and quantity of groundwater

Water / water heat pumps whose primary source of thermal energy is groundwater are typically provided by an open system of two wells. The water drawn from the pumped well is subject to qualitative and quantitative requirements [8]. In terms of groundwater quality, ie its purity and chemical composition, the basic monitoring parameters with most of the heat pumps are the same because the water quality affects only those parts of the primary circuit of the pump that are in direct contact,so pipe duct and evaporator (plate heat exchanger) [9].

The cleanliness of the water used and the elimination of most of the solids can be ensured by installing the filter and its regular cleaning to prevent the clog, heat transfer degradation, and hence reducing the efficiency of the heat pump [10].

Qualitative indicators of chemical composition of water include [9], [10], [11]:

- pH - if it is low, the water is aggressive and able to dissolve some metals,
- hardness - evaluation of the amount of Ca and Mg,
- aggressive CO2 - a free CO2 form capable of etching surfaces, increasing the aggressiveness of water,
- electrical conductivity - expression of salt content in water, eg. chlorides and sulphates,
- Fe and Mn values - their increased presence in water can make to corrode the parts of the device.

The specific requirements of individual selected HPs from different manufacturers, or distributors, for groundwater quality, are usually to the installation manuals of the device..

In terms of quantitative conditions, each HP has its own recommended flow as in the primary so and secondary circuits, and these data are part of the technical parameters (see Table 1). The flow along with the water temperature in the primary part of the heating system must be monitored regularly, because in case of limiting or interrupting the flow, the efficiency of the heating system is reduced or the heating system switches off completely,

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and the water in the evaporator can freeze at a low temperature of the heat source. Negative consequences can be the damage of the evaporator to the accident at which the working medium escapes. That is why in this section, it is customary to install flow detectors, respectively, flow meters that shut off the compressor in case of inadequate flow of water and stop the operation. In order to avoid similar complications, a pumping test is performed prior to the installation of HP the water / water type, which determines the richness of the groundwater source (wells). However, the success of this test does not guarantee a steady flow over a longer period of time [10].

Table 1 Selected HP arranged according to the recommended flow rate

Type HP	COP	Flow [m^3.h^{-1}]
NIBE 5 kW	4,09	0,65
NIBE 6 kW	4,17	0,72
NIBE 8 kW	4,46	1,08
G-TERM 5006.3	5,08	1,1
G-TERM 5007.3	5	1,5
NIBE 12 kW	4,3	1,55
G-TERM 5008.3 Ai	5,07	1,6
G-TERM 5009.3	5,3	1,9
BUDERUS WPW90 I / G-TERM 5011.3	5,1 / 4,83	2
G-TERM 5010.3 Ai	5,29	2,1
G-TERM 5014.3 Ai	5,25	2,9
BUDERUS WPW140 I	5,2	3,3
G-TERM 5017.3 Ai	5,59	3,6
G-TERM 5021.3 Ai	5,61	4,4
BUDERUS WPW210 I	5,5	5
G-TERM 5024.3 Ai	5,71	5,1
G-TERM 5027.3 Ai	5,7	5,8
BUDERUS WPW270 I	5,1	7
G-TERM 5062.3	5,13	7,2
G-TERM 5072.3	5,17	8,3
BUDERUS WPW440 IP	5,9/5,7	9,5
G-TERM 5089.3	5,17	10,3
G-TERM 5109.3	5,15	12,6
BUDERUS WPW920 IP	5,9/5,4	20

5 Methodics

In the previous section, we had defined requirements, respectively. limits of the most important quantitative and qualitative indicators which is necessary to pay attention when considering over HP with an open water / water system whose primary source of thermal energy is groundwater. Adhering to the recommended values of these indicators should ensure not only efficient operation but also a longer service life device. Subsequently, we analyzed these indicators in groundwater on the territory of the Slovak Republic using the groundwater Atlas map created by ŠGÚDŠ in 2011. The output of this analysis is the follow-up information, which was also processed by ArcGis software, and thus were obtained the below mentioned of maps outputs. It is clear that the geological component of the rock environment in which groundwater is found has a significant influence on the values of our monitored indicators.

The steps we have chosen can be summarized as follows:

1.We found out which indicators are primarily observed for underground water used by the heat pump - temperature, flow, chemical composition.

2.We have selected 25 heat pumps from 3 manufacturers - Buderus, Nibe and G-Term Slovakia. The individual pumps belong to different power categories, they have different COP and, in particular, the recommended flow rates are different. Based on the available information, it is assumed that the water quality requirements are the same.

3. Subsequently, we have individually surveyed values at selected points in each hydrogeological zone for each indicator in the map application, which is freely available on the ŠGÚDŠ website. To get real results, we chose 3 to 6 points, averaged the values which we obtained and assigned geographic coordinates to each point. They allowed us to create maps in the ArcGis softwer and showing the territory of Slovakia which is and which is not in accordance with our qualitative and quantitative conditions.

4. After completing the above steps, we were able to review our findings. In addition to the course of the individual indicators in the SR, we could use the filter of the MS Excel and find on the obtained data:

- the highest value of the indicator,
- the lowest value of the indicator,
- the total average value of the indicator in the whole territory of our state,
- the most frequently occurring indicator value in Slovakia,
- which indicators in individual zones are higher/ lower than our conditions and thus constitute an obstacle to using groundwater in water / water heat pump.

By doing so, we should fulfill our main objective and determine where hydrogeological zones are suitable to place our heat pumps which groundwater utilizing and where it is not appropriate due to unfulfilled conditions.

6 Evaluation

6.1 Quantitative indicator of groundwater

The quantitative indicator that was considered in the article and which we consider to be important for the HP activity is the inflow. We found out that (Figure 2, Figure 3):

Highest detected value: 118,35 m3.h-1
Lowest detected value: 0,12 m3.h-1
Total average value: 6,72 m3.h-1.
The most common value (modus): 5,4 m3.h-1.

Almost every one of the 25 HPs has a different recommended minimum flow rate. For ease of assessment of our findings, we have aligned heat pumps from the smallest to the largest required groundwater flow (see Table 2). We have assumed that if the HP has a recommended minimum flow rate of 0.65 $m^3.h^{-1}$, they are also possible use in zones with the flow rate 2 and 8 $m^3.h^{-1}$ respectively because it can be controlled relatively simply by for example with a throttle valve.

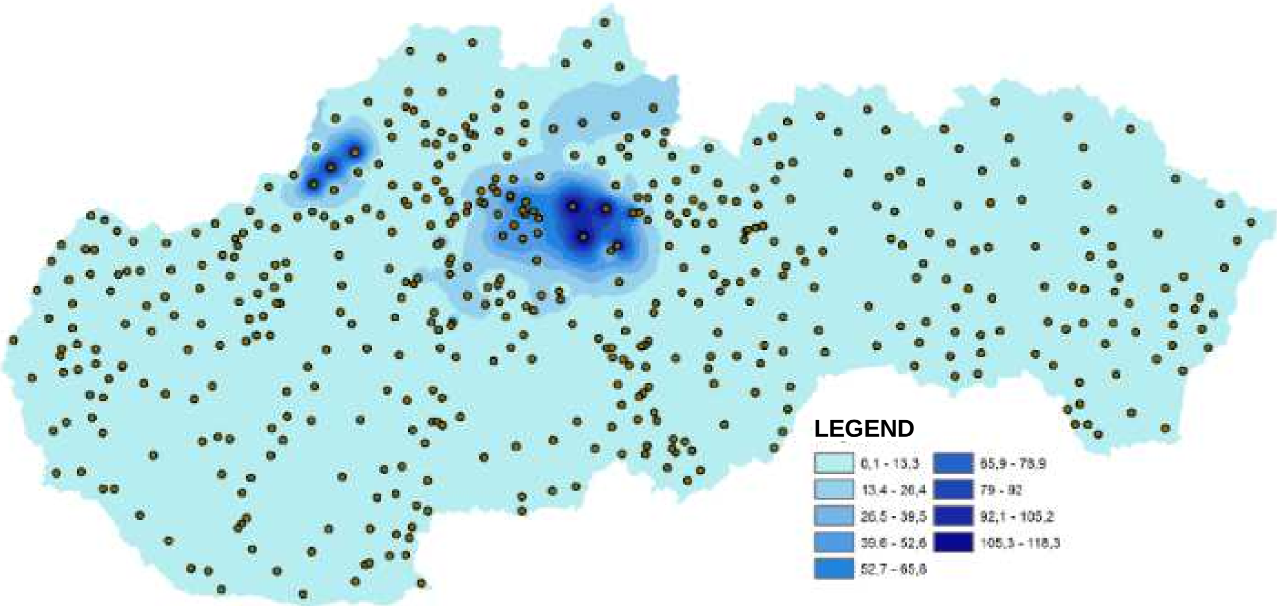

Figure 2 Flow of groundwater in Slovakia (processed according to[12]

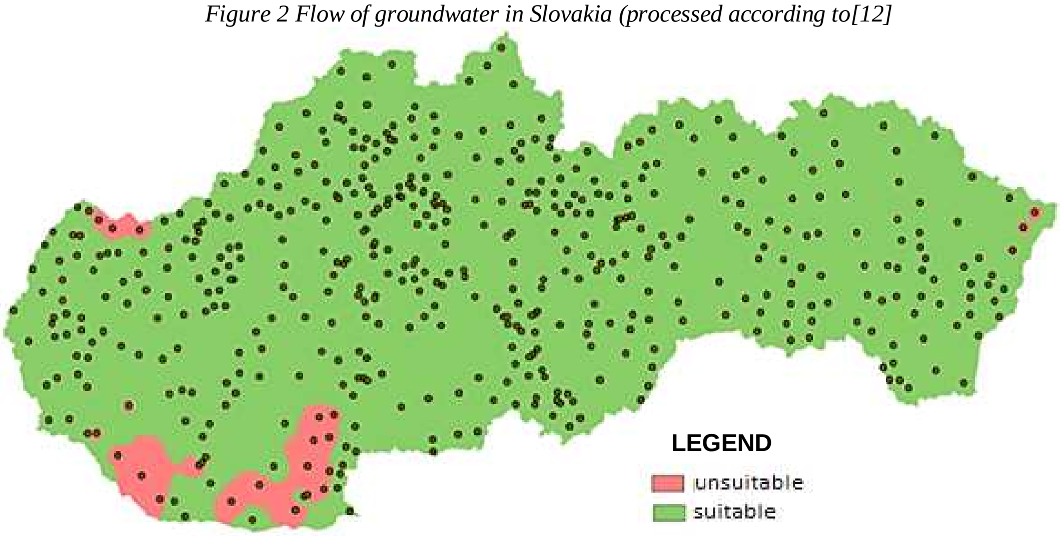

Figure 3 Territory suitable/unsuitable with flow requirements (processed according to [12])

6.2 Qualitative indicators of groundwater

The suitability of the hydrogeological zones for HP from the point of view of quality was evaluated according to the manufacturer's technical manuals, focusing on groundwater temperature and chemical composition. In their assessment, we have focused on the boundary values of individual elements or compounds towards which not only the steel parts of the evaporator but also the copper ones are resistant to corrosion, incrustation and total evaporator degradation.

6.2.1 Temperature

The lowest appropriate temperature for the HP we took into consideration was 7 °C. We have found that the groundwater of Slovakia in most of the zones meets this condition, and even in some places are achieving significantly higher temperatures (Figure 4, Figure 5).
Highest detected value: 15,2 °C
Lowest detected value: 4,8 °C
Total average value: 10,6 °C
The most common value (modus): 9 °C

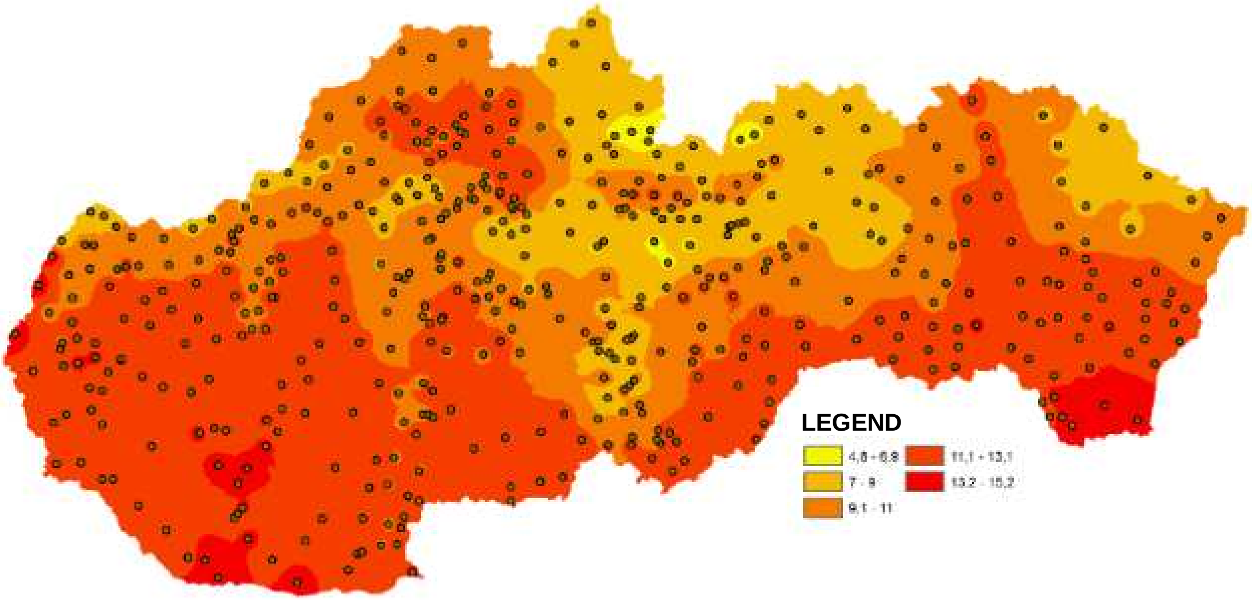

Figure 4 Groundwater temperature at SR (processed according to [12])

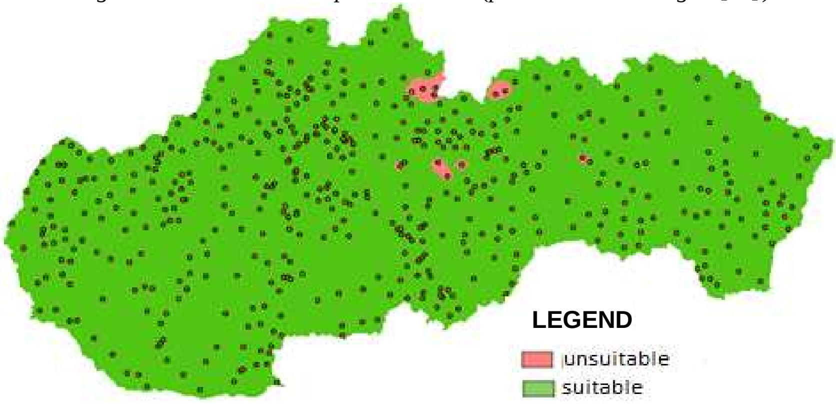

Figure 5 Territory suitable/unsuitable with temperature requirements (processed according to [12]

6.2.2 Iron

The limit value for this element is 0.2 mg.l^{-1}. If the iron concentration in groundwater is higher, the risk of corrosion also increases. It is one of the main indicators that are monitored in the water for your HP (Figure 6, Figure 7).

Highest detected value: 0,85 mg.l^{-1}
Lowest detected value: 0,01 mg.l^{-1}
Total average value: 0,44 mg.l^{-1}
The most common value (modus): 0,74 mg.l^{-1}

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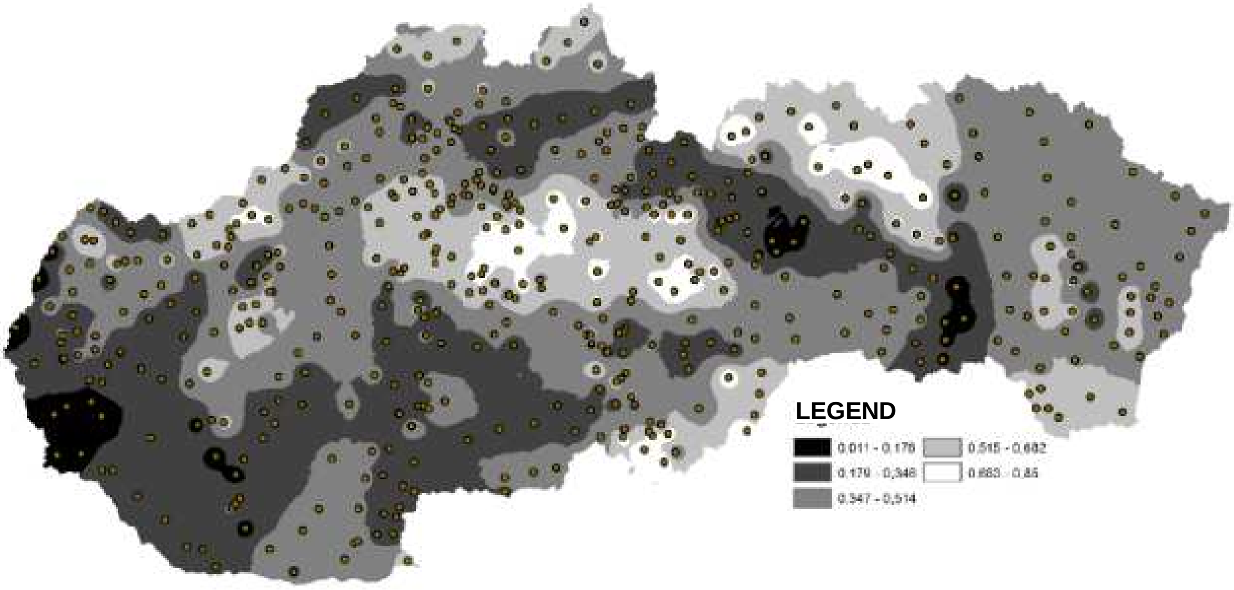

Figure 6 Quantity of iron in groundwater of Slovakia (processed according to [12])

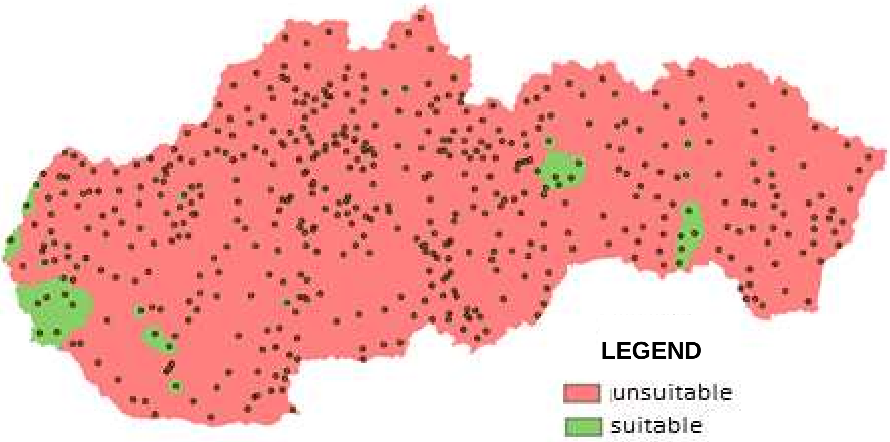

Figure 7 Territory suitable/unsuitable with iron requirements (processed according to [12])

6.2.3 Manganese

Since it is commonly found with iron, it is the second important indicator of the chemical composition of water. Its limit value, which should not be exceeded, is 0,1 mg.l^{-1} (Figure 8, Figure 9).

Highest detected value: 1,67 mg.l^{-1}

Lowest detected value: 0,01 mg.l^{-1}

Total average value: 0,30 mg.l^{-1}.

The most common value (modus): 0,02 mg.l^{-1}

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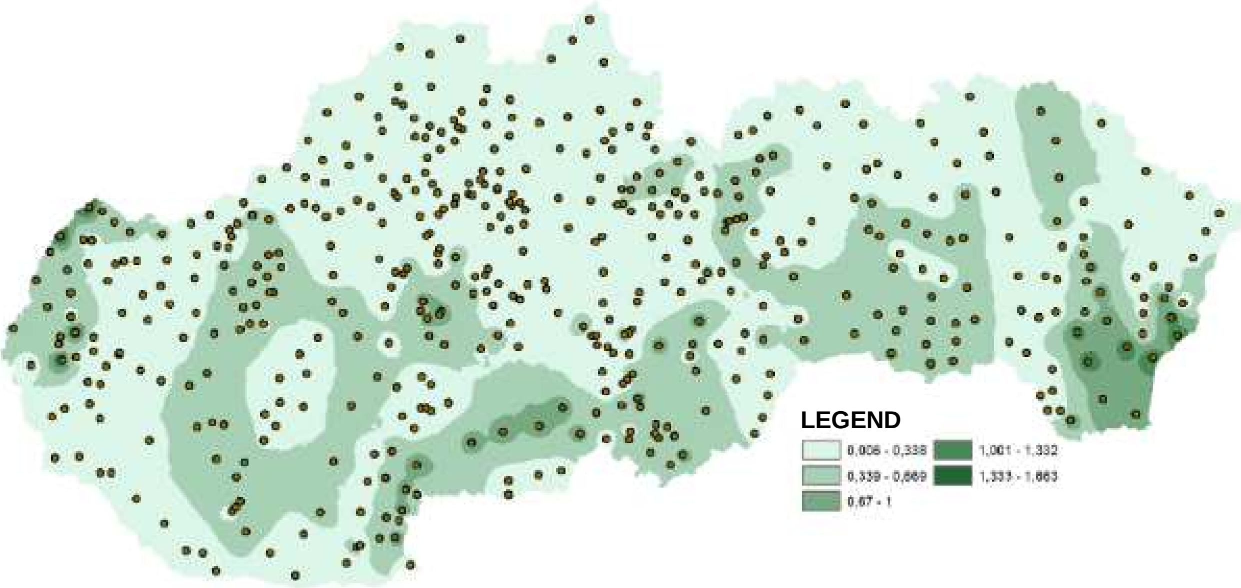

Figure 8 Quantity of manganese in underground waters of Slovakia (processed according to [12])

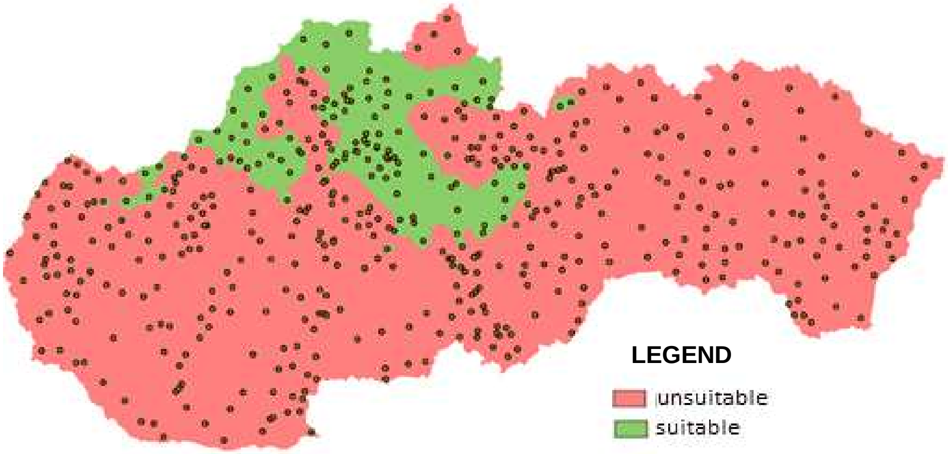

Figure 9 Territory suitable/unsuitable with manganese requirements (processed according to [12]

6.2.4 pH value

Like for many other devices, are does not suit to heat pumps too acidic or too alkaline water. The recommended values of BUDERUS are 7.5 - 9 [10] (Figure 10, Figure 11).

Highest detected value: 10,6
Lowest detected value: 7
Total average value: 8,2.
The most common value (modus): 8,8.

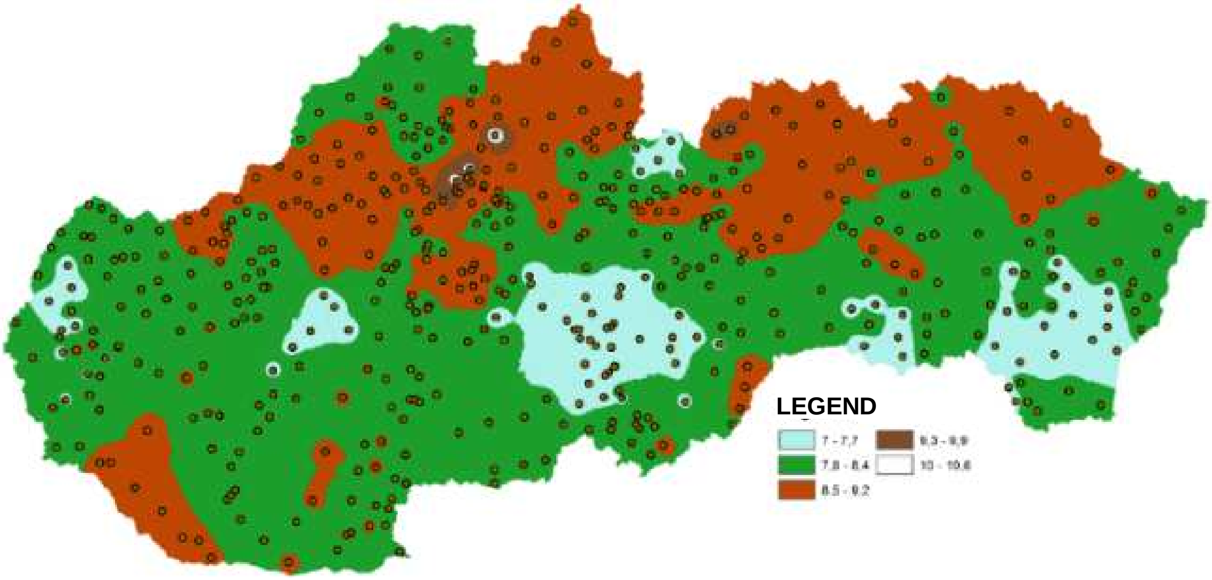

Figure 10 pH values of underground waters of Slovakia (processed according to [12])

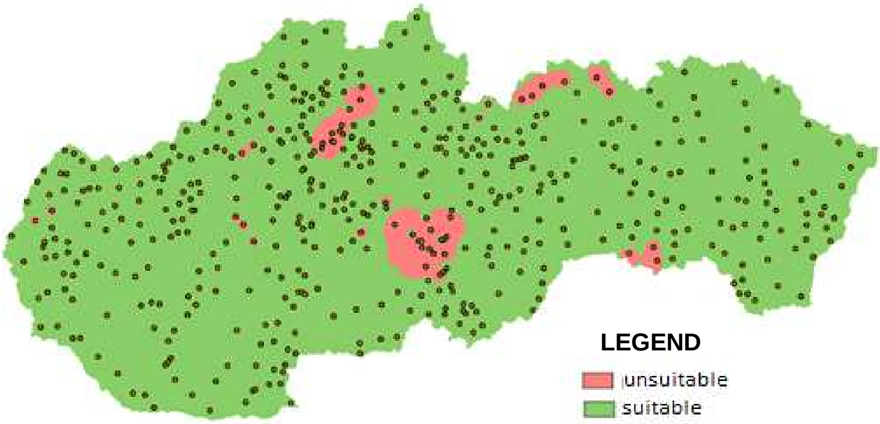

Figure 11 Territory suitable/unsuitable with pH requirements (processed according to [12])

6.2.5 Hardness of water

Too hard water is not suitable for the evaporator, as limestone deposits can occur, respectively scale in. It is recommended that water reaches a maximum of 4,5 mmol.l^{-1} (Figure 12, Figure 13).

Highest detected value: 13,23 mmol.l^{-1}
Lowest detected value: 0,30 mmol.l^{-1}
Total average value: 4,32 mmol.l^{-1}.
The most common value (modus): 10,71 mmol.l^{-1}.

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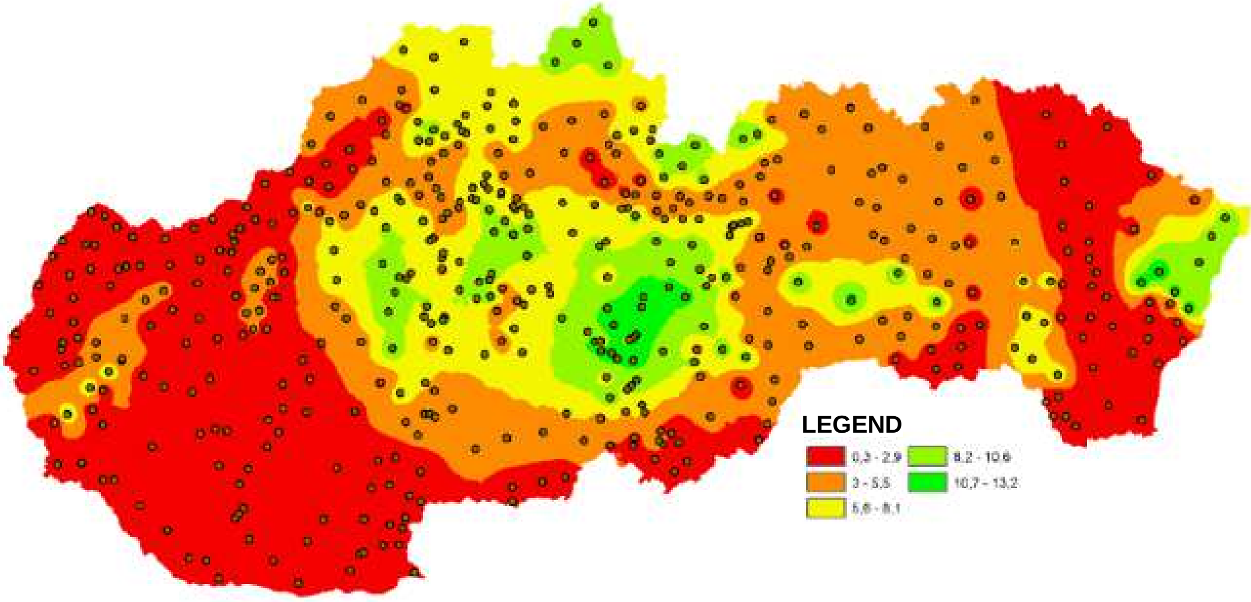

Figure 12 Hardness of groundwater in the SR (processed according to [12])

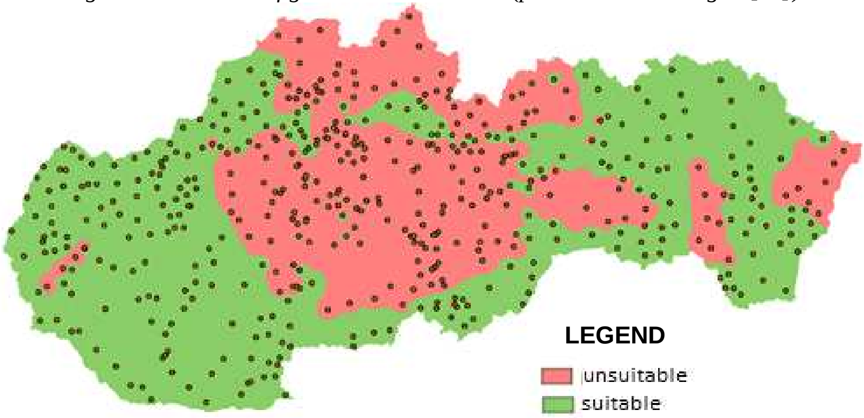

Figure 13 Territory suitable/unsuitable for hardness requirements (processed according to [12])

6.2.6 Bicarbonates

In order to avoid the occurrence of incrustations in the evaporator and the source water was not too hard, the concentration of bicarbonates should be in the range of 70-300 mg.l^{-1}. Only about 1/3 of the zones meet this requirement, typically value is less than 70 mg.l^{-1} (Figure 14, Figure 15).

Highest detected value: 452,55 mg.l^{-1}
Lowest detected value: 11,77 mg.l^{-1}
Total average value: 84 mg.l^{-1}.
The most common value (modus): 19,32 mg.l^{-1}.

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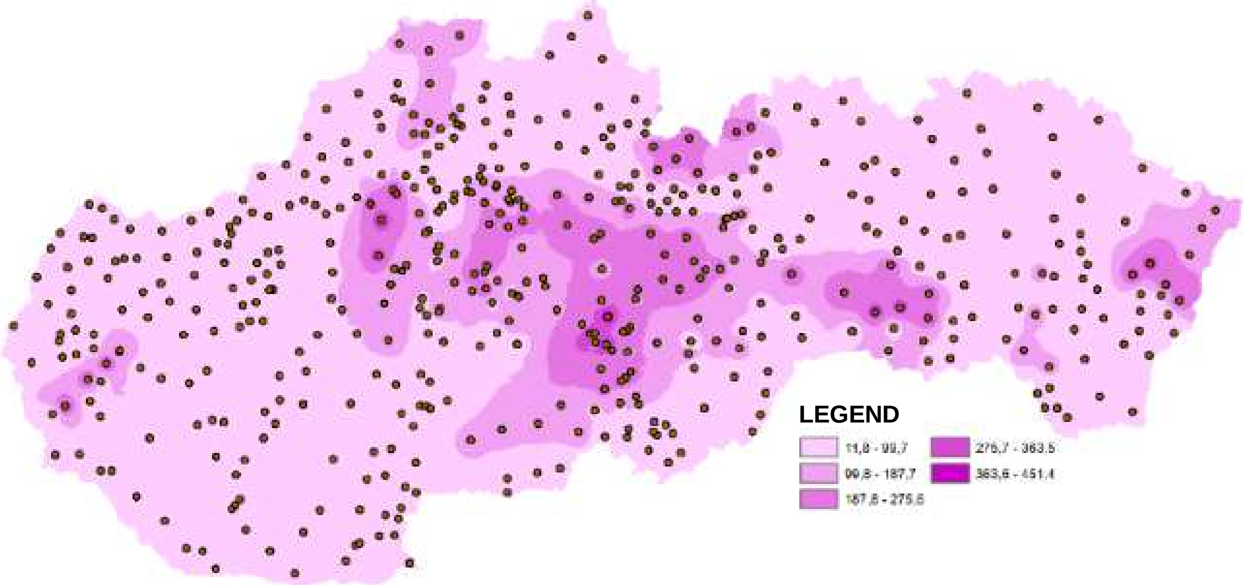

Figure 14 Concentration of HCO_3 in groundwater (processed according to [12])

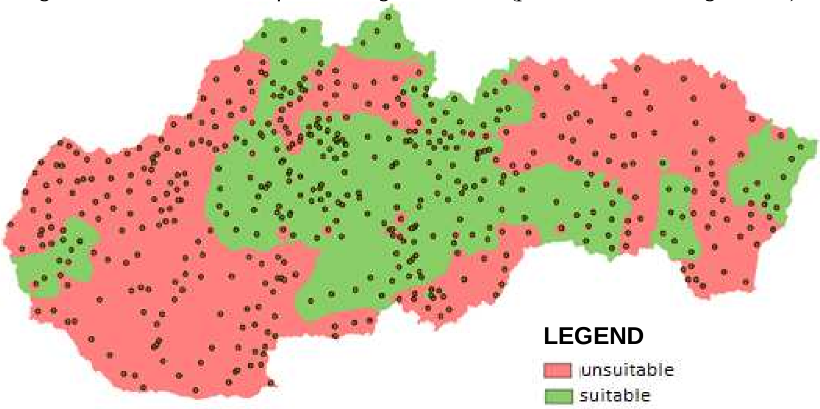

Figure 15 Territory suitable/unsuitable with HCO_3 requirements (processed according to [12])

6.2.7 Sulfates

It is not recommended at sulphates that their concentration in groundwater exceeds 70 mg.l^{-1} Higher quantities may indicate that groundwater is contaminated (Figure 16, Figure 17).

Highest detected value: 174,39 mg.l^{-1}
Lowest detected value: 2,83 mg.l^{-1}
Total average value: 38,91 mg.l^{-1}.
The most common value (modus): 62,17 mg.l^{-1}.

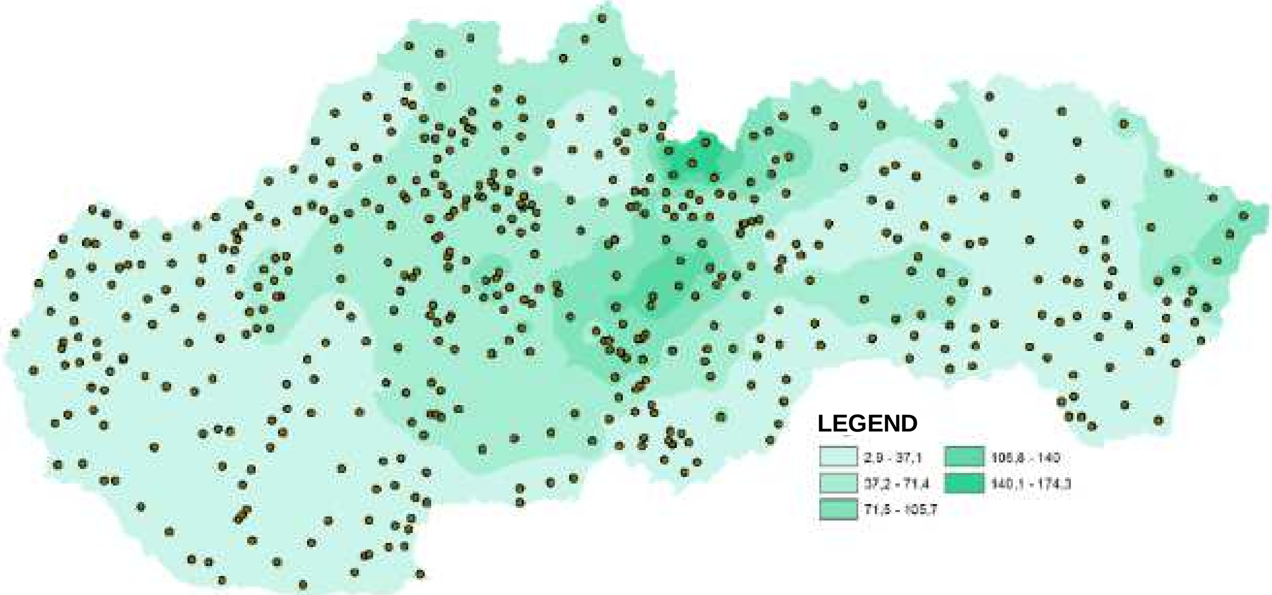

Figure 16 SO_4 quantity in groundwaters SR (processed according to [12])

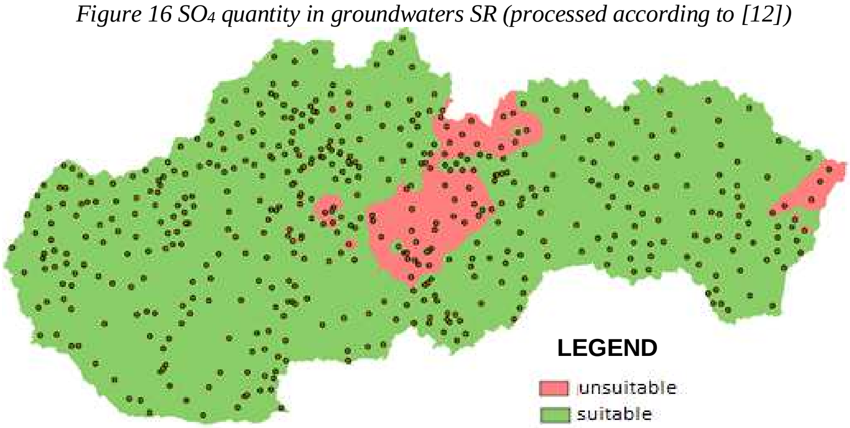

Figure 17 Territory suitable/unsuitable with SO_4 requirements (processed according to [12])

6.2.8 Aggressive CO_2

So as groundwater flowing to the evaporator not should to be too aggressive, the concentration of aggressive CO_2 should be less than 25 mg.l^{-1}. Higher concentration notice water is already considered aggressive by [13] (Figure 18, Figure 19).

Highest detected value: 53,66 mg.l^{-1}
Lowest detected value: 0,32 mg.l^{-1}
Total average value: 14,29 mg.l^{-1}.
The most common value (modus): 27,32 mg.l^{-1}.

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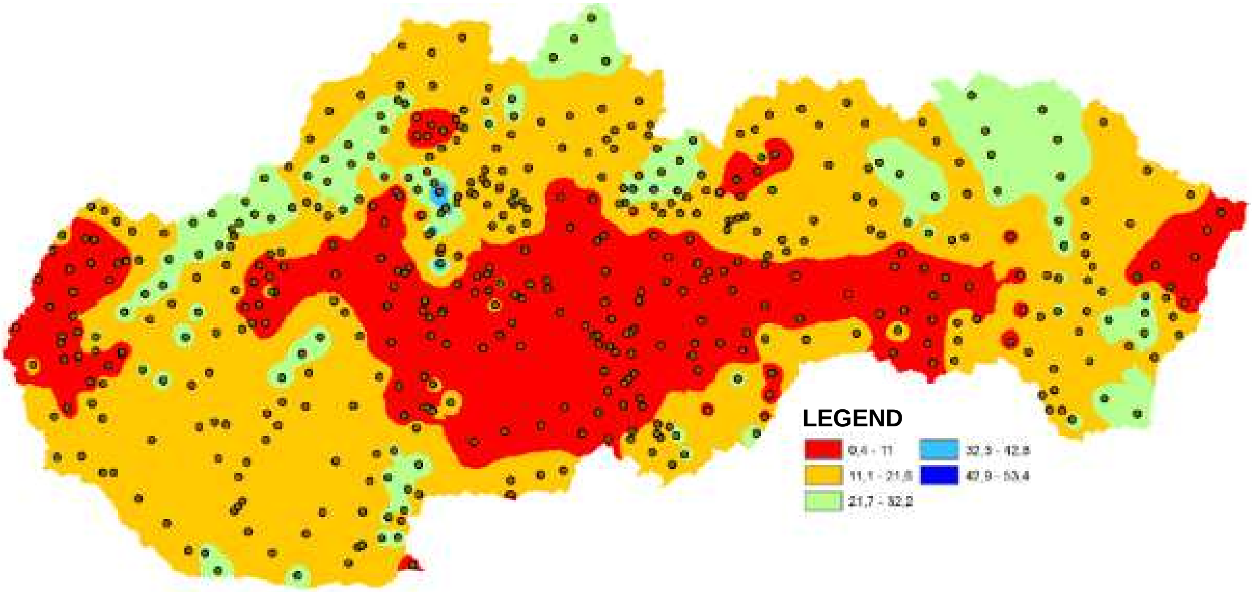

Figure 18 The amount of aggressive CO_2 in groundwater of the SR (processed according to [12])

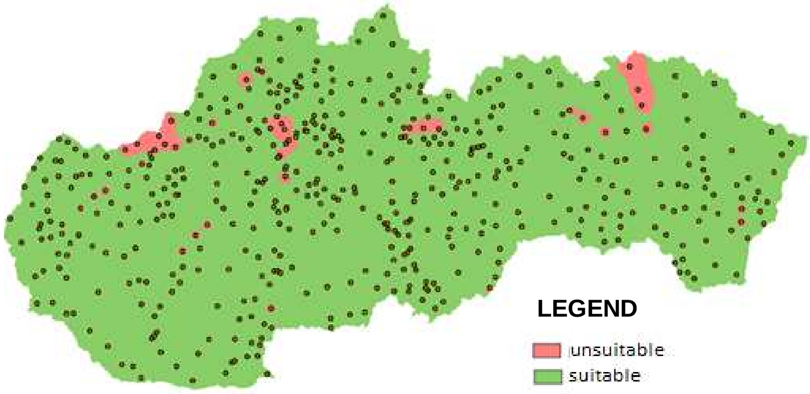

Figure 19 Territory suitable/unsuitable with aggressive CO_2 requirements (processed according to [12])

6.2.9 Electrical conductivity

The electrical conductivity (also referred to as EC), is a good indicator of water pollution similar like sulphates. Its recommended values are 10-500 μS.cm^{-1} (Figure 20, Figure 21).

Highest detected value: 1888,3 μS.cm^{-1}
Lowest detected value: 86,2 μS.cm^{-1}
Total average value: 630,13 μS.cm^{-1}.
The most common value (modus): 657,89 μS.cm^{-1}.

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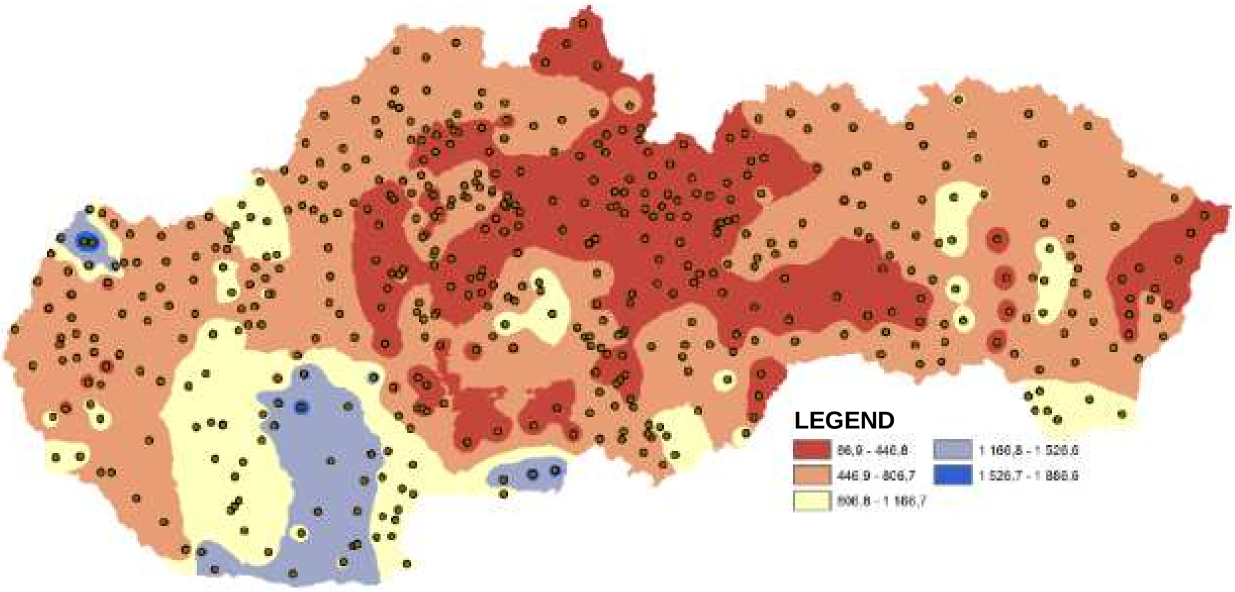

Figure 20 Electrical conductivity in underground waters of Slovakia (processed according to [12])

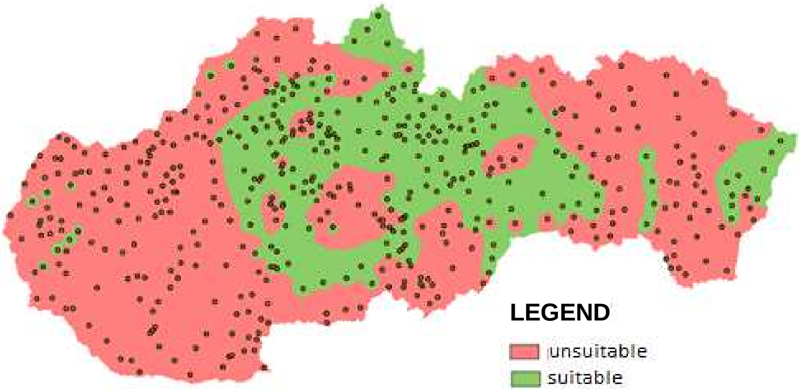

Figure 21 Territory suitable/unsuitable for electrical conductivity requirements (processed according to [12])

6.2.10 Chlorides

The chlorine concentration in groundwater used by HP should be less than 300 $mg.l^{-1}$ (Figure 22, Figure 23)

Highest detected value: 90,51 $mg.l^{-1}$

Lowest detected value: 2,00 $mg.l^{-1}$

Total average value: 25,89 $mg.l^{-1}$.

The most common value (modus): 3,42 $mg.l^{-1}$.

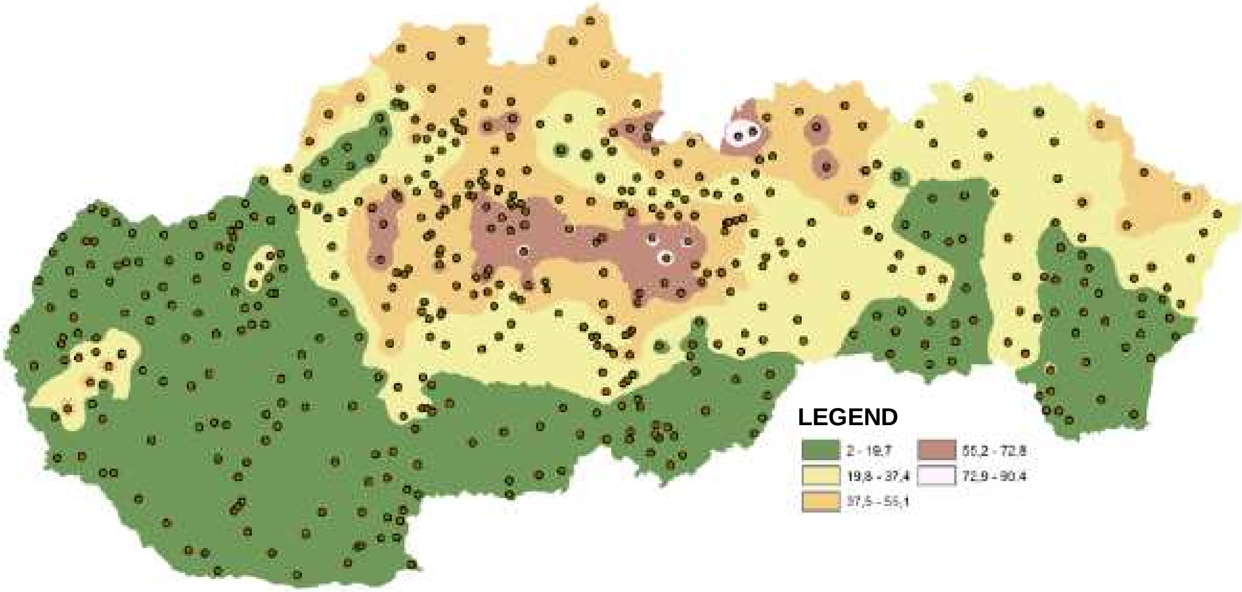

Figure 22 The amount of chlorides in groundwater of Slovakia (processed according to [12])

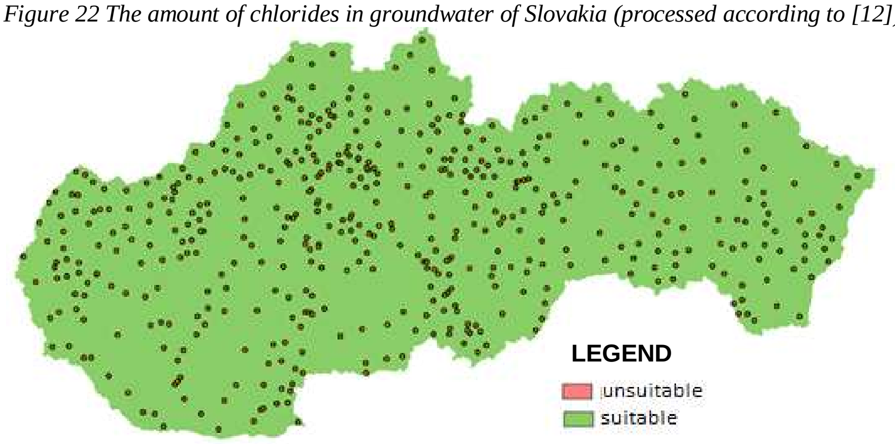

Figure 23 Territory suitable/unsuitable for chlorides requirements (processed according to [12])

6.2.11 Nitrates

The amount of nitrate in the water, that is the heat source for HP should be less than 100 mg.l^{-1} (Figure 24, Figure 25).

Highest detected value: 27,96 mg.l^{-1}

Lowest detected value: 0,68 mg.l^{-1}

Total average value: 10,00 mg.l^{-1}.

The most common value (modus): 19,32 mg.l^{-1}.

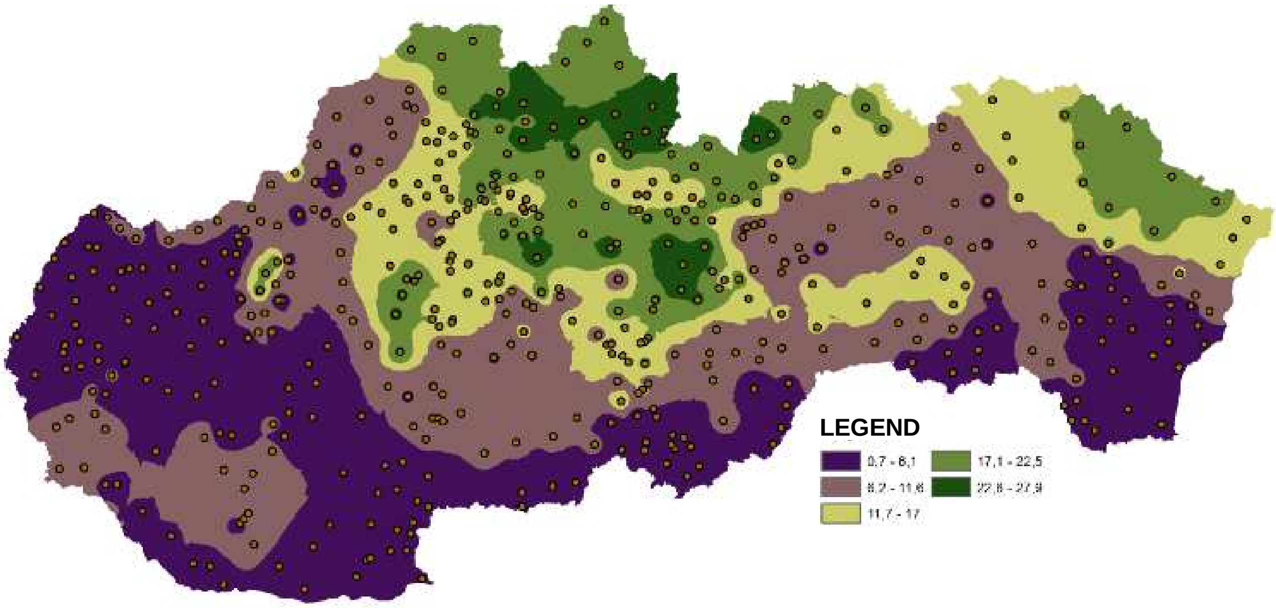

Figure 24 Concentration of nitrates in groundwater of SR (processed according to [12])

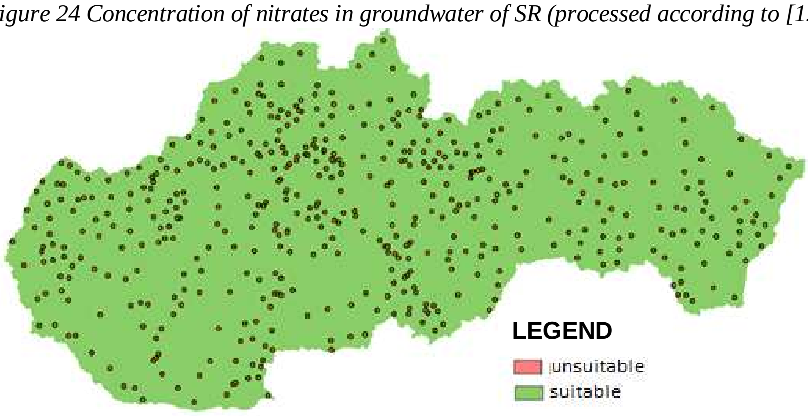

Figure 25 Territory suitable/unsuitable for NO3 requirements (processed according to [12])

6.2.12 Aluminum

The concentration of aluminum in groundwater, as well as iron, should not exceed 0.2 mg.l^{-1} (Figure 26, Figure 27).

Highest detected value: 0,428 mg.l^{-1}
Lowest detected value: 0,008 mg.l^{-1}
Total average value: 0,07 mg.l^{-1}.
The most common value (modus): 0,008 mg.l^{-1}.

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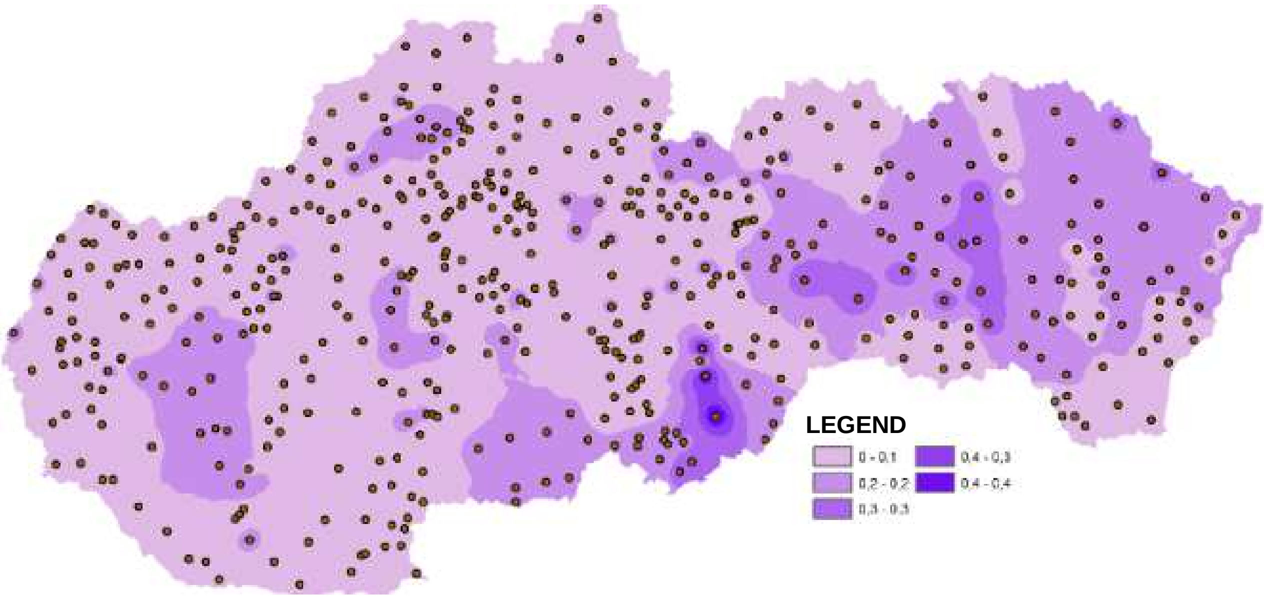

Figure 26 Amount of aluminium in groundwater SR (processed according to [12])

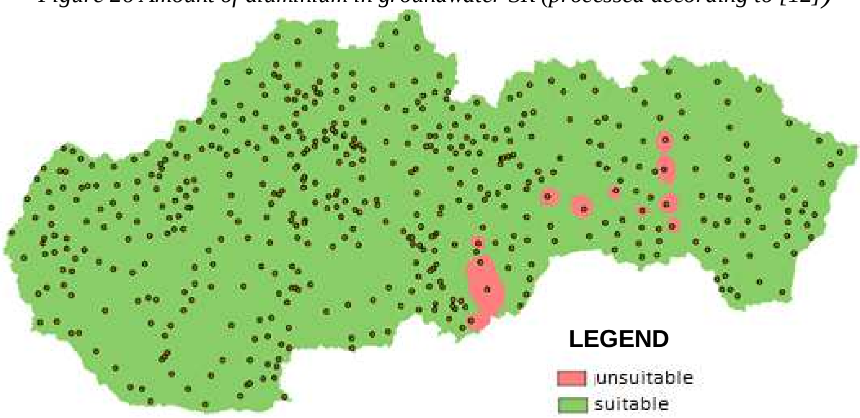

Figure 27 Territory suitable/unsuitable for Al requirements (processed according to [12])

Graph no. 2. (Figure 28) shows how many zones have higher or lower values of individual indicators than are recommended by manufacturers, distributors, resellers, or heat pump installers, and therefore do not meet HP's requirements for the quality and / or quantity of groundwater used.

The graph shows that 120 hydrogeological zones in Slovakia have higher iron values than 0.2 mg.l^{-1}, 99 zones have manganese concentrations higher than 0.1 mg.l^{-1}, 96 zones have lower or higher bicarbonate content, such as the recommended range of 70-300 mg.l^{-1} and 95 zones, has an electrical conductivity higher than 500 µS.cm^{-1}. Increased hardness was found in 54 zones. Exceeding these indicators significantly increases the risk of corrosion of the evaporator.

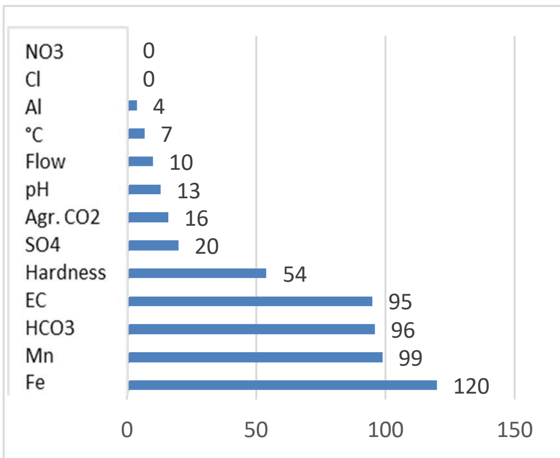

Figure 28 Number of hydrogeological regions not meeting the individual surveyed indicators

Regarding the flow, we found in ten zones that the well capacity of the wells, respectively boreholes in the given areas is less than 0.65 m^3.h^{-1}. This would significantly negatively affect the operation and effectiveness of HP (Figure 29, Figure 30).

A lower temperature than 7 °C was detected in only 7 zones, which means that this indicator should not be a major problem for HP installation in our territory.

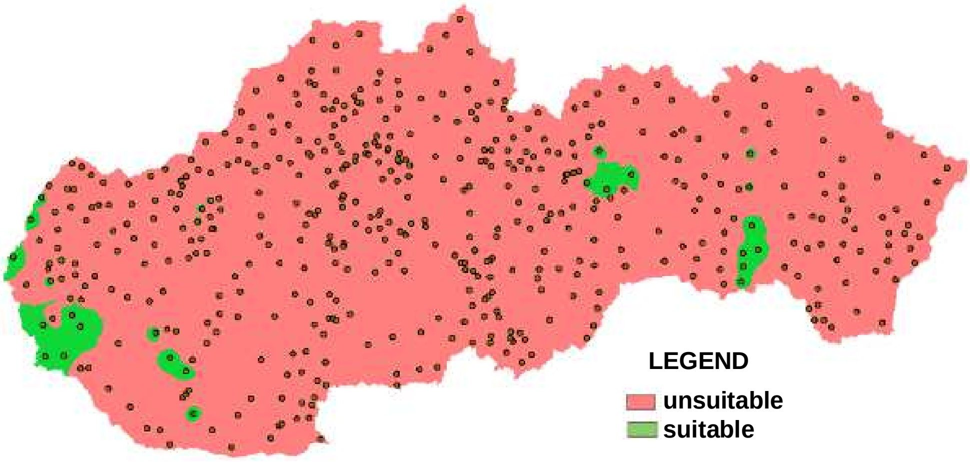

Figure 29 Areas suitable/unsuitable the requirements for t, p, Fe, pH, hardness (processed according to [12])

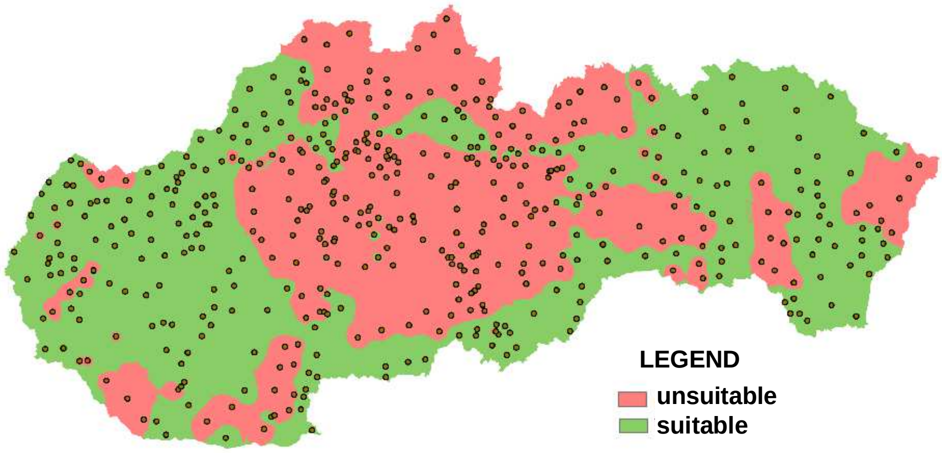

Figure 30 Areas suitable/unsuitable the requirements for t, p, pH, hardness (processed according to [12])

Conclusion

Finally, we can state that the ground waters of Slovakia in terms of temperature are very suitable for use by heat pumps, as its values often range from 7 to 15 °C. In terms of quantity, respectively, flow, depends substantially on the particular location where the heat pump will be installed, although the flow should be sufficient in most of the area, at least four devices with lower output. From the point of view of quality, most groundwater in our territory is not suitable for direct use by heat pumps, due to the high probability of corrosion in the primary part of the system circuit, but after the treatment (softening) of the water used afterwards using heat pumps is very appropriate, efficient and environmentally acceptable.

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VERIFICATION OF OPERATING CHARACTERISTICS OF PNEUMATIC ARTIFICIAL MUSCLES WITH THE REAL TIME CONTROL SYSTEM

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Keywords: PAM, vibrations, PWM
Abstract: The article describes an experimental device based on the antagonistic involvement of pneumatic artificial muscles, a draught for changes of the experimental device, made to provide possibilities for a more fluid operation of the device and at the same time measurement of the operational characteristics. The article also describes a test measurement performed to verify its performance characteristics using a wide-pulse modulation.

1 Introduction

Research and development in the field of manufacturing technology is continually driven by new challenges from manufacturing companies and companies focusing on manufacturing machines and handling equipment. Efforts to maintain a strong competitive environment lead manufacturers of production technologies to look for new solutions to manufacturing nodes and to introduce modern technologies into production. Currently, for example, there are requirements for modern production operations, capable of fulfilling its function even in aggressive environments. Or vice versa, there is a need for a technical device, with an adapted drive for an environment where standard types of drive can not be used for their negative impact on the working environment [1],[2],[3],[4],[5].

In today's manufacturing plants, companies often go through automation. In view of development trends such as the Industry 4.0 concept, it is important for automation to take into account structural management as well as to implement modular management elements and network interconnection of individual elements of the production system into its structure. Within the manufacturing system elements, pneumatically-operated production facilities are not an exception. For pneumatic actuators, drive based on the Pneumatic Artificial Muscle (PAM) is now commonplace [1],[6],[7].

The article describes an online control system for an experimental actuator based on the antagonistic involvement of pneumatic artificial muscles (PAMs). The aim of this work is to propose a methodology for online monitoring, measurement of dynamic characteristics and control of systems operating on a similar principle, in order to achieve optimal operation of the equipment, in the stage of basic management utilization, previous implementation of advanced control functions. The control system was created using LabVIEW graphical programming software. The designed control program uses hardware from National Instruments company for its operation. In order to transport the compressed medium into the transport system between the pressurized medium source and the pneumatic artificial muscles, are used electropneumatic valves which allows pulse-width modulation (PWM) [4], [7].

2 Description of the Experimental Involvement and Its Amendments

2.1 Original experimental device

In Figure 1 is a depicted experimental facility comprising antagonistic involvement of pneumatic artificial muscles.

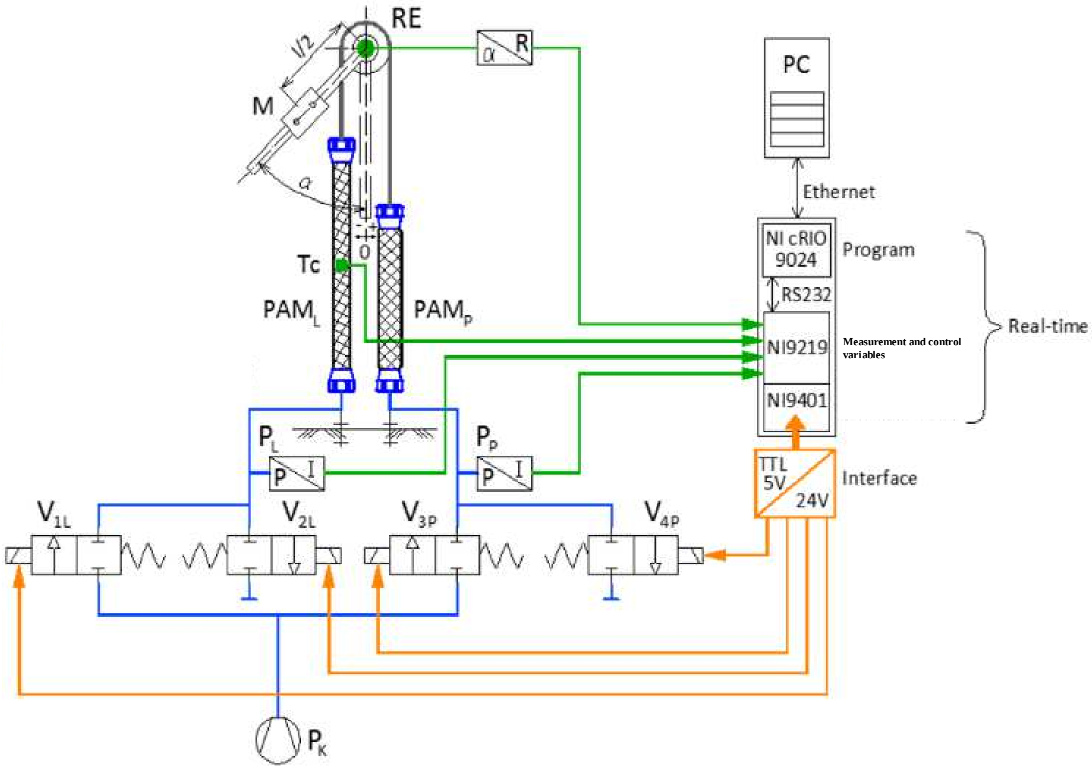

Figure 1 Experimental assembly of PAMs in antagonistic assembly [4]

Description of the image: PAM_L/PAM_P – pneumatic artificial muscle left/right, M – weight, RE – position sensor, α - the angle of rotation of the arm from the zero (vertical) position, Tc – thermocouple, R – electric resistance, PC – Control stand, P_L/P_P – pressure sensor left/right, P – pressure, I – electric current, V_{1L}/V_{3P} – inflation electro-pneumatic valve left/right, V_{2L}/V_{4P} – deflation electro-pneumatic valve left/right, PK – pressure at the compressor output.

The above diagram of the device shows that there are constantly monitored pressure in PAMs, the size of the carrier arm rotation and the left muscle temperature, during the operation of the device.

Assembly management is provided by a real-time control system, consisting of NI CompactRIO components, designed for real-time monitoring, diagnostics and control. The control system algorithm itself was designed in the LabVIEW Real Time graphical development environment. The PC provides the user with the ability to monitor the progress of the measured variables while controlling the device in the user environment of the program [7].

After the initial experiments were completed [4], the experimental device had to be modified for future integration into more complex systems, to eliminate its limitations and to do redeeming. The original system included temperature measurement on the left PAM via a thermocouple. This method of measuring the temperature did not suit the used analog-to-digital converter. Measurement of the temperature on the surface of the pneumatic artificial muscle in the vertical position and with the inlet and outlet of the air at its lower part was not equally suitable for several reasons. During operation, the thermocouple was able to measure the temperature of only one point on the PAM surface. Due to the PAMs structure and its function, the temperature of each point at the shape of the PAM was different. For this reason, an alternative was chosen where the surface temperature of the PAM will be measured thermographically in the future. The previous scheme also does not allow control of the movement of the carrier arm, except for the use of feedback control using the mathematical model of the PAM system.

2.2 *Modified Experimental facility*

For a more detailed monitoring of the operating conditions of the equipment, the original system was supplemented by measuring the acceleration of the support arm in the directions of its movement and also in the forward direction of the carrier arm, in the event of imperfect connection of the drive shaft with the support arm and also to detect any mechanical failure of the device.

The new design of the experimental device is shown in Fig. 2. Thermal sensor temperature sensing was left to test the accuracy of the proposed system. Later it was removed [8].

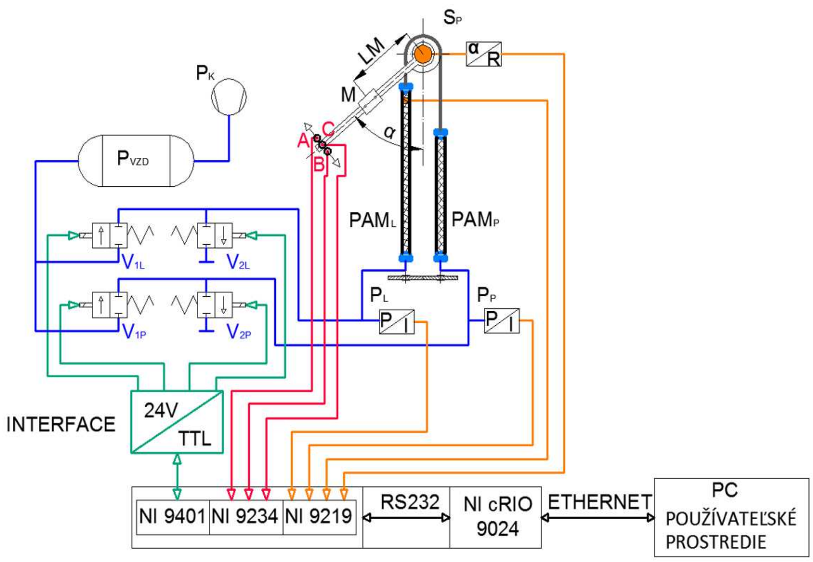

Figure 2 Modified experimental device assembly with PAMs [7]

Image description: PAM_L – left PAM, PAM_P – right PAM, LM -the center of gravity of the load-bearing member M from the pivot arm shaft, S_P – potentiometric position sensor, α – angle of arm rotation from zero position, P_L – left pressure sensor, P_P – right pressure sensor, P – pressure, I – electric current, R – electric resistance, P_K – pressure at the compressor output, V_{1L} / V_{1P} – left/right inflation electro-pneumatic valve, V_{1L} / V_{1P} – left/right deflation electro-pneumatic valve, P_{VZD} – pressure in the pressure vessel, A/B/C – acceleration sensors. The orange wires represent the signals from the original sensors, the red wires represent vibration sensor signals, the green wires are used for control signals for electropneumatic valves and the blue color represent the cross connection between the PAMs and pressure vessel [7]. After the experimental device modifications were processed, experimental measurements were performed to describe the operating conditions of antagonistic involvement of PAMs.

3 Experimental Measurements Results

PWM utilization allows smaller rotation of the support arm as well as it has partial impact to a change in the speed of its movement. The disadvantage of pneumatic systems is the interconnection of their parts with the need for lower pressure of the working medium with the source of the pressurized working medium with higher pressure. At low pressure in both PAMs, when the electropneumatic valves are opened, pneumatic impacts occur which, can lead to undesirable overhang of the support arm, at the time of acceleration and deceleration of the support arm.

The partial results from the experimental measurement are shown in Fig. 3. The carry arm was positioned in to position of 15 ° from its zero vertical position where the working pressure in both PAMs is at the lowest level. In this case was the positioning arm starting from the minimum working pressure setting level in both PAM. The results are shown in the iterations of the repeating control program.

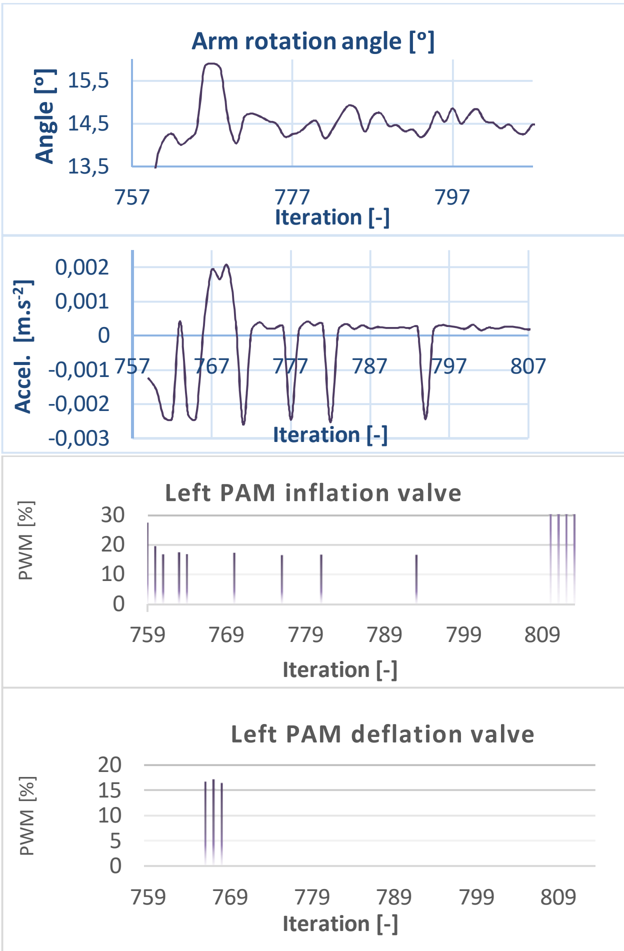

Figure 3 Results of experimental measurements

The results of the experimental measurement showed that the justification of the application of the acceleration sensors for monitoring the events taking place inside the pneumatic system.

The experimental measurement results show the dependence between the opening of the electropneumatic valve and the acceleration of the support arm. Also, the dependence between the acceleration of the carry arm and the deviation (overlap) of the actual position of the carry arm from the required position, can be seen. This deviation is a result of carry arm movement with the corresponding acceleration and the number of iterations of its duration.
With the system's low stiffness, the positioning accuracy of the end element of the device is significantly influenced by the number of iterations (duration) during which the electropneumatic valve is open.

Conclusions

An experimental device with a drive based on the antagonistic assembly of pneumatic artificial muscles was designed and modified, at the Department of Process Engineering. This article describes the schema of individual parts of the assembly, in its original and in its modified form, and one of a series of measurements performed to verify the functionality of the proposed real-time control system. Results of the measurements performed on the device have shown the justification for the implementation of the acceleration sensors to the actuator system. Vibration sensing has provided the control program with greater flexibility and improved capabilities of the drive based on the antagonistic involvement of pneumatic artificial muscles, to control the performance of the device during deceleration and acceleration. However, all this advantages are performed at the expense of the time required to handle the workpiece. In the future, it is necessary to minimize the measured values to the minimum necessary level, to optimize the calculation time required to execute one iteration of the control program, to analyze the time requirements for transmitting signals within the mechatronic system using current hardware, and possibly replacing the components with their faster alternatives. At the same time, after modifying the system, the module for control of the carrier arm position can be replaced, for instance with algorithms for Fuzzy logic control.

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