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Generation of Nitrogen Oxides in Submerged Arc Furnace during the Production of Ferroalloys

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Abstract: The paper presents the method of selection of hard coals applied in reducing mixtures used in ferroalloy production technologies. The graphical relationship between reflectivity and reactivity towards SiO as well as reflectivity and the content of hard carbon C_{fix} has been presented. The use of hard coal in place of coke is associated with the release of significant amounts of volatiles contained in the coal. Increasing the amount of volatile matter may favor the increased generation of NO_x from the fuel mechanism due to the nitrogen content in the organic matter of coal. The influence of the thermal mechanism of NO_x generation may be limited due to contradictory phenomena. On the one hand, it is possible to have a higher calorimetric combustion temperature of post-reaction gases (due to the content of coal degassing products), and on the other hand, reducing the amount of energy released from SiO afterburning (less SiO due to higher silicon yields). The higher yield of silicon is related to the higher reactivity of appropriately selected hard coals. The mechanisms of NO_x formation were presented together with measurements made during the production of the most popular ferroalloy FeSi75. Measurements were carried out along the two axes P1 and P2 in the furnace hood at three distances from the center of the pitch diameter of the electrodes.

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1 Introduction

Ferrosilicon smelting is a continuous process carried out in the submerged arc furnaces with the Søderberg self-baking electrodes [1-3]. Respectively granulated raw materials are charged into the furnace from the top, in the form of the mixture batch consisting: quartzite, carbon reducers (hard coal, coke and wood chips), carriers of iron (mill scale or iron chips). One of the most important structural elements of the ferrosilicon furnaces are immersed in the charge electrodes which bring electricity required for the process. Most often these are self-baking Søderberg electrodes [2]. Necessary heat for the highly endothermic reduction reactions of silica is generated through resistive heating direct in the furnace charge as a result of current flow, and through arc radiation in the arc gas chambers located near the electrodes tip. Periodically, approximately at equal time intervals molten metal is tapped into the ladle, through one of the tap holes located in the side wall near to the furnace hearth. A significant impact on the efficiency of the process have got metallurgical conditions of reaction zones, in particular the appropriate balance of coal and heat distribution in the reaction zones.

Due to their properties, ferroalloys (ferrosilicon, ferromanganese, ferrochrome) are widely used in the metallurgical and chemical industries [1,2]. The most popular ferroalloys are ferrosilicons (FeSi65 and FeSi75), used in the steel industry for steel deoxidation and as alloy additives.

The carbon reducer in the process of smelting ferroalloys with the electrothermal reduction method is the source of carbon involved in the reduction processes and affects the physical properties of the batch mixture.

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The use of carbon reducers in the form of hard coal mixtures in the production of ferroalloys may be the cause of an increased generation of nitrogen oxides from the technological process. For the formation of nitrogen oxides is responsible the mechanism of fuel and thermal oxides. It should be expected that in a properly conducted technological process the advantage constitute oxides generated by the fuel mechanism. Occasional SiO combustion above the charge surface as a result of uncontrolled gas discharge from the lower reactor in the air oxidizing atmosphere causing local temperature rise and generation of thermal nitrogen oxides. The incidental occurrence of such a phenomenon suggests its minor importance in the total NO_x emissions. In the upper layer of the charge, the temperature is lower than that considered necessary for the occurrence of the thermal NO_x, and additionally there is a reducing atmosphere, rich in CO [4].

The aim of this work was to present the method of selecting hard coals applied in reducing mixtures used in ferroalloy production technologies, to describe the potential mechanisms of NO_x formation and to measure the composition of post-process gases, with particular emphasis on NO_x.

2 Aspects of the selection of carbon reducers

The possibility of using a wide range of carbon reducers, from coke through mixtures of hard coal to charcoal in the production of ferroalloys, requires their proper selection. Leading producers of ferroalloys, by choosing hard coals for the process, in addition to paying attention to the previously mentioned parameters and the content of C_{fix} hard carbon, perform additional measurements. They are to determine the qualitative suitability of a given raw material for production. Such measurements include the determination of the reactivity of the tested hard coal towards SiO [5].

The measurement method used is very burdensome for the sake of serious difficulties in generating SiO gas, which then reacts with the tested reducer. The method was developed by the SINTEF research foundation founded in 1950 and adopted as the standard reaction test. This method is burdensome, and not without significance are the high costs of the apparatus and the costs of electricity necessary to carry out the tests. During the research on the suitability of coals for the electrothermal smelting of ferroalloys, mainly by the SINTEF method, a relationship between the reactivity towards SiO and the reflectivity of the carbons was found [5]. The evaluation of the characteristics of coals useful for the silica reduction process was confirmed not only by laboratory tests, but also by observations in industrial facilities. In simplified terms, it can be assumed that carbons with low reflectivity are characterized by better reactivity towards SiO. During their tests using the SINTEF method, less unreacted gaseous SiO flowed into the afterburning chamber to SiO_2, which was shown in Figure 1 [6]. The graphical

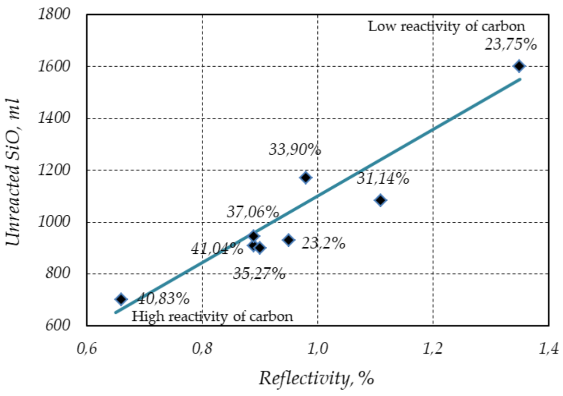

Figure 1 Dependence between reactivity to SiO and coal reflectivity (next to the point, values of dry, ash-free volatile matter in % were placed) [6]

relationship presented in Figure 1 is extremely important for determining the expected technological properties of new coal grades without the need to perform complicated and onerous SINTEF tests.

Determining the vitrinite reflectivity in carbon according to the standards is much simpler and cheaper. In the selection of a carbon reducer, apart from technological aspects, an economic criterion is also important. In chemical reactions essential for obtaining the final product takes part the so-called hard carbon C_{fix}. Therefore, in the economic aspect, it is important to select such carbon reducers which apart from high reactivity are characterized by the highest possible C_{fix} content. Figure 2 shows the dependence of the C_{fix} content in hard carbon on the reflectivity during selection of carbon reducers. Using Figures 1 and 2, hard coals with good reactivity and appropriate C_{fix} content can be distinguished. However, it should also be taken into account that hard coal is a mineral of organic origin with variable properties, even if it comes from the same seam [7]. Changing the type of reductant from metallurgical coke with low volatile content to hard coal or their mixture caused the appearance of a significant amount of volatile components above the charge surface. This phenomenon may contribute to the increased concentration of nitrogen oxides generated from the fuel mechanism in post-process gases.

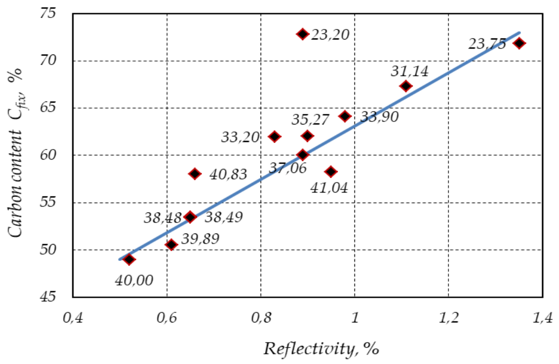

Figure 2 Dependence between carbon C_{fix} contents and coal reflectivity (next to the point, values of dry, ash-free volatile matter in % were placed) [6]

3 Mechanisms of nitrogen oxides formation

Nitrogen content in coal is 0.5% to 2% [8], reaching maximum for elemental carbon C^{waf} = 85% [9]. Coal typically contains 1% to 2% of nitrogen with bituminous coals usually containing 1.5–1.75% and anthracites mostly containing less than 1%. The presence of nitrogen in coal has not been fully understood and described yet. There is far better knowledge of the structures of sulphur and oxygen than those of coal-nitrogen. Due to difficulties encountered in investigations of nitrogen content in coal, indirect methods of analysis are used and structures present in coal extracts or high-temperature coal tars are determined. A structural formula of one nitrogen binding in the coal matrix is shown in Figure 1 below [10].

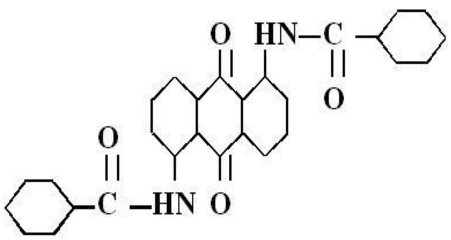

Figure 3 A structural formula of one nitrogen binding in the coal matrix[10]

The product of primary pyrolysis, nitrogen-containing volatile matter, undergoes secondary pyrolysis to produce HCN, NH_3, CN and N_2. HCN, NH_3 and CN are oxidised to NO_x and N_2O. One part of N_2 is formed directly during pyrolysis, while the other is formed through NO_x reduction by hydrocarbon radicals or in a reaction with CO.

The composition of nitrogen-containing volatile matter (HCN, NH_3, NO_x) is influenced by coal types. Studies related to oxygen deficiency (λ = 0.5–0.8) revealed that in case of anthracite, only NO_x (and not HCN or NH_3) was formed in the amount of 17.5%. For bituminous coals, the amount of HCN is higher than that of NH_3 and increases with the increase in coal volatile matter content to produce 6–11% of NO_x. Low-rank coals (subbituminous coals and lignites) release the highest amounts of NH_3 and HCN, but less NO_x than bituminous coals. The studies of model nitrogen-containing liquid combustion showed a similar conversion of different types of compounds into NO_x [11]. Many studies suggest that emissions of specific coal nitrogen compounds during combustion are strongly related to the reaction stoichiometry. Air deficiency promotes N_2 formation, while its excessive amounts lead to NO_x formation [12].

Complex mechanisms of nitrogen oxide formation during coal combustion have been classified using the source of nitrogen and divided into two basic groups [13-15]:

- fuel processes: oxidation of nitrogen compounds that are chemically bound with the fuel organic matter,
- thermal processes: reactions of atmospheric nitrogen with atomic oxygen that is produced at high temperatures.

Historically, the first homogeneous mechanism of NO formation is a thermal mechanism. The thermal mechanism of nitrogen oxide formation from molecular nitrogen is a sequence of chemical reactions that occur independently of the combustion process.

After a series of experiments conducted in a flow reactor at 1653 K to 1798 K, Tomeczek and Gradoń [16] proposed a concept of extended thermal mechanism. Measured NO concentrations were far higher than those calculated according to the Zeldowicz mechanism [13]. The authors proposed the extended thermal mechanism based on five reactions: two reactions were adopted from the Zeldowicz mechanism [13] and three reactions were adopted from the N_2O mechanism developed by Malte and Pratt [17].

Nitrogen that is chemically bound with the fuel releases from coal during devolatilisation or during char combustion. In case of devolatilisation, nitrogen mainly moves to the gaseous phase as hydrogen cyanide HCN. Due to rapid oxidation, the compound is primarily transformed into NCO and NH_i radicals. Miller et al. [18] presented a cycle of fuel-nitrogen transformations into NO or N_2 in the following simplified scheme:

$$\textbf{Fuel nitrogen}\quad \mathbf{N \Rightarrow HCN \Rightarrow NCO \Rightarrow NH_i \Rightarrow N} \begin{matrix} \Rightarrow \mathbf{NO} \\ \Rightarrow \mathbf{N_2} \end{matrix}$$

In general, mechanisms of fuel-nitrogen oxide formation are assumed to poorly depend on temperature, contrary to

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thermal NO formation [19]. Fuel-NO_x plays a key role during coal combustion within the temperature range of 1500–2000 K [9].

4 Measurement of composition of post-process gases

Below are the measurements of the composition of post-process gases at a height of 2 m above the edge of the furnace tub, while the exhaust gases are discharged through the bypass. Figure 4 shows the location of points where furnace gas analyzer probe was introduced.

Table 1 Composition of post-process gases above the edge of the furnace bath [20]. The composition of the post-process gas was measured with the IMR 3000 P exhaust gas analyzer equipped with electrochemical sensors: O_2 with a range of 0 ÷ 20.9%, CO with a range of 0 ÷ 60,000 ppm, SO_2 with a range of 0 ÷ 4,000 ppm, NO with a range of 0 ÷ 2,000 ppm, NO_2 with a range of

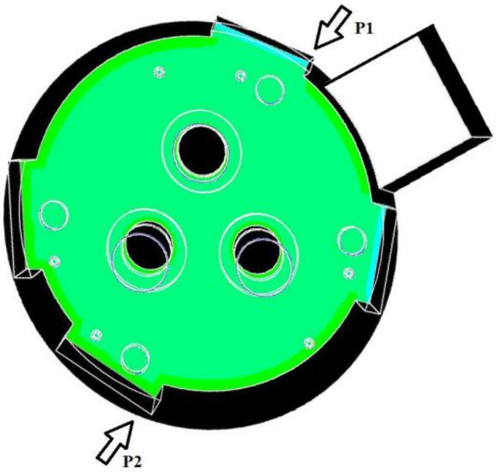

Figure 4 Location of points where furnace gas analyser probe was introduced

0 ÷ 4,000 ppm. Due to the large range of the CO sensor in the IMR 3000 P, the WAG-1 analyzer was used in parallel, which was equipped with sensors: electrochemical CO with a range of 0 ÷ 2,000 ppm, electrochemical O2 with a range of 0 ÷ 100%, FTIR CO2 with a range of 0 ÷ 100%, FTIR CH4 with a range of 0 ÷ 100%. The temperature was measured with a K-type thermocouple placed in the aspiration probe. The measured values were similar to those read from the temperature sensor placed in the probe of the IMR 3000 P exhaust gas analyzer.

Table 1 Composition of post-process gases above the edge of the furnace bath [20]

Distance from the furnace axis - 2,75 m			
Gas temperature		Point 1	Point 2
		414°C	396°C
Component		Value	
O_2	%	20,0	20,2
CO_2	%	1,9	1,8
CO	ppm	50	80
CH_4	%	0,1	0,2
NO	ppm	35	82
SO_2	ppm	2	1
Distance from the furnace axis - 2,25 m			
Gas temperature		Point 1	Point 2
		366 °C	220 °C
Component		Value	
O_2	%	19,9	19,7
CO_2	%	1,5	2,4
CO	ppm	40	40
CH_4	%	0,2	0,1
NO	ppm	17	10
SO_2	ppm	3	1
Distance from the furnace axis - 1,90 m			
Gas temperature		Point 1	Point 2
		299 °C	270 °C
Component		Value	
O_2	%	20,3	19,9
CO_2	%	1,1	1,1
CO	ppm	20	20
CH_4	%	0,2	0,1
NO	ppm	16	36
SO_2	ppm	3	1

5 Conclusions

Appropriate verification of hard coals used in the technology of ferroalloys production may contribute to the reduction of their consumption in the input materials.

Initial verification is proposed to be carried out with the use of vitrinite reflectivity as a quantity related to the reactivity towards SiO.

The presence of volatile components in the reducer may favor the generation of nitrogen oxides associated with the fuel mechanism.

Reducing the amount of SiO in post-reaction gases, as a result of the higher reactivity of the coals used, lowers their combustion temperature, which may have a positive effect on the reduction of nitrogen oxides generation related to the thermal mechanism.

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The reference list

[1] SCHEI, A., TUSET, J.K., TVEIT, H.: *Production of High Silicon Alloys*, Tapir, Trondheim, 1998.

[2] ZUBOV, V.L., GASIK, M.I.: *Electrometallurgy of Ferrosilicon. Physical Chemistry and Technology*, Dnenpropetrovsk, System Technologies Publlication, 2002.

[3] STRUŃSKI, B.M.: *Rasczety rudo-termiczeskich pieczi*, Izdatielstwo Metallurgia, Moskwa, 1982.

[4] RYPDAL, K.: Uncertainties in the Norwegian emission inventories of acidifying pollutants and volatile organic compounds, *Environmental Science & Policy*, Vol. 5, pp. 233–246, 2002.

[5] RAAMES, O., GRAY, R.J.: *Coal in the production of silicon rich ferroalloys*. Proceedings International Ferroalloys Congress, INFACON VII, Trondheim, pp. 201−220, 1995,

[6] MACHULEC, B., BIALIK, W.: *Properties of carbon reducers for the electrothermal smelting of ferrosilicon*, Katowice, 2014 (unpublished work).

[7] KWIATKOWSKI, E.: *Outline of the chemical technology of hard coal*, Państwowe Wydawnictwo Techniczne, Warszawa, 1954.

[8] TINGEY, G.L., MORREY, J.A.: *Coal structure and reactivity*, A Battelle Energy Program Report. Battelle Pacific Northwest Laboratories, Richland, Washington, 1973.

[9] RYBAK, W.: *Coal structure and pollutant emissions during combustion*, PKBP Conference on Research and Technology, Ustroń, pp. 13-26, 1996.

[10] VAN KREVELEN, D.W.: *Coal*, Elsevier, Amsterdam, 1981.

[11] STAŃCZYK, K.: Chemistry of nitrogen in coal and formation of nitrogen oxides during coal and char combustion – a review, *Koks Smoła Gaz,* Vol. 11, pp. 260-264, 1991.

[12] BRUISMA, O.S.L., GEERTSMA, R.S., OUDHUIS, A.B.J., KAPTEIJN, F., MOULIJN, J.A.: Measurement of C, H, N - release from coals during pyrolysis, *Fuel*, Vol. 67, pp. 1190-1196, 1988.

[13] ZELDOWICZ, Y.B.: The oxidation of nitrogen in combustion and explosions, *Acta Phisicochemica USSR*, Vol. 21, pp. 577-628, 1946.

[14] FENIMORE, C.P., JONES, G.W.: Nitric oxide decomposition at 2200-2400 K, *The Journal of Physical Chemistry*, Vol. 61, pp. 654-657, 1957.

[15] TOMECZEK, J., GRADOŃ, B.: The role of nitrous oxide in the mechanism of thermal nitric oxide formation within flame temperature range. *Combustion Science and Technology*, Vol. 125, pp. 159-180, 1997.

[16] TOMECZEK, J., GRADOŃ, B.: The role of N_2O and NNH in the formation of NO via HCN in hydrocarbon flames, *Combustion and Flame,* Vo. 133, No. 3, pp. 311–322, 2003.

[17] MALTE, P.C., PRATT, D.T.: *Hydroxyl radical and atomic oxygen concentrations in high-intensity turbulent combustion*, 16th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, pp. 145-155, 1977.

[18] MILLER, J.A., BRANCH, M.C., MC LEAN, W.J., CHANDLER, D.W., SMOOKE, M.D., KEE, R.J.: *The conversion of HCN to NO and N_2 in H_2-O_2-HCN-Ar flames at low pressure*, 20th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, pp. 673-684, 1984.

[19] MILLER, J.A., BOWMAN, C.T.: Mechanism and modeling of nitrogen chemistry in combustion, *Progress in Energy and Combustion Science,* Vol. 15, pp. 287-338, 1989.

[20] BIALIK, W., MOCEK, P.A.: Preliminary tests of selected thermal-flow parameters of a modern resistance-arc furnace for ferrosilicon smelting. *Hutnik*, Vol. 78, No. 9, pp. 728−731, 2011.

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Automatic Corrector of Forming Operations on High Speed Forging Machines

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Abstract : When forging rods with diameters larger than 200 mm, excessive wear of the anvils often occurs. Worn anvils then inaccurately measure the continuous dimensions of forged bars. In response, it has been proposed to develop a new aiming method, which should use a laser camera to determine the inter-operational dimensions of the forged bars, taking into account the wear of the anvils. This information would be used to correct the forging algorithm and thus to refine the final forging operations.

Citation: Sikora Kamil: Automatic Corrector of Forming Operations on High Speed Forging Machines, Advance in Thermal Processes and Energy Transformation, Volume 4, No.3 (2021), pp. 42-44, ISSN 2585-9102

1 Introduction

The main idea of refining forging operations is to use the correction of the automatic program of forming operations of high-speed forging machines (RKS) using laser aiming. When forging shafts on high-speed machines, the anvils always wear out over time. In addition to the forming itself, these anvils also serve to measure the current diameter of the forged shaft from their current position. As these anvils wear in the order of millimeters, the required measurement accuracy is not guaranteed after a certain period of use. The proposed device uses the input image data from the camera to control the anvils and move the forging press so that the output of the forging is a forging of the desired shape. The solution is limited to forging rotationally symmetrical forgings [1].

2 Description of the innovated technology

For this purpose, a system for automatic alignment of the forged shaft using a NIR camera (camera operating in the near-infrared region) was developed. The output from the camera is a luminance image, which is transferred via gigabit Ethernet in the source data to the control computer and further processed there. With the help of specially developed computer vision algorithms, a 3D model of the forging is reconstructed (a rotationally symmetrical body is assumed). The control system of the high-speed forging machine uses data from the described camera system to correct the actual dimensions of the forged shaft and then adjusts the forging mode in real time with regard to the detected wear of the anvils and the current shape of the forging [2, 3].

Figure 1A Photo of a 3D laser camera

Figure 1B Photo of a Basler camera

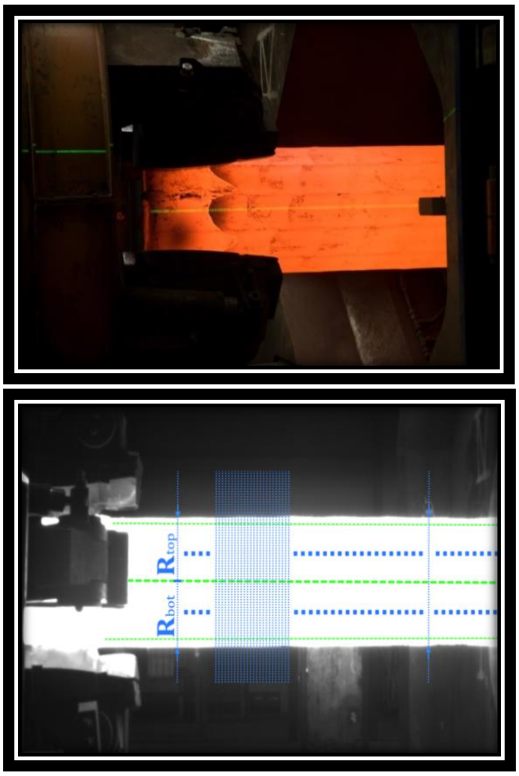

Figure 2 Photo of the focus and display of the forging in the scene

3 Practical application

The final practical use of the aiming system in forging was experimentally created at the workplace of the VÍTKOVICE HAMMERING a.s. high-speed machine, where the aiming is performed in the manner described above. The introduction of this measurement correction system created the possibility of automatic calibration of the anvil distance during the immediate forming process and also allows the operator to accurately control the dimensions and roughing allowances in real time.

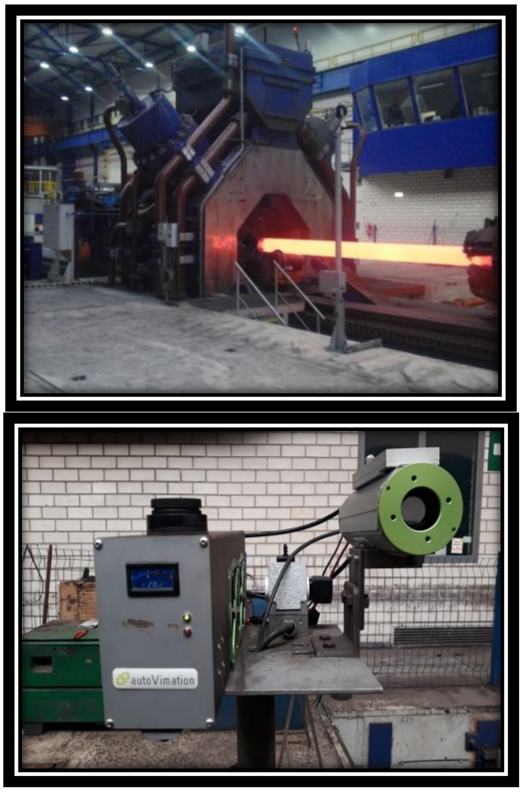

Figure 3 Photo of the high-speed machine and the camera with the cooler

The camera itself is mounted on a special pole and is automatically guided to a moving forging. Data from a specially cooled camera communicates in real time with the Siemens control system. This method of immediate automatic correction of the control system of the high-speed forging machine using current data of forging dimensions (correcting the wear of anvils) has not been used in the Czech Republic so far. Thanks to this fact, the Industrial Property Office of the Czech Republic awarded this technology a utility model under number 32 227 entitled: Equipment for continuous wear correction of high-speed machine anvils.

4 Rod fitting D400mm new technology

On the figures shows the assembly before starting the forging. The rounded ingot on the D700mm is located between the anvils of the high-speed forging machine from the edge. In Figure 4, the blank is shown in a 3D view after the first pass. The total deformation is set for automatic numbering. Figure 5 shows the second passage when forging through 8 edges at D620mm in section. Figure 6 is a 3D view of the third pass after 8-edge forging.

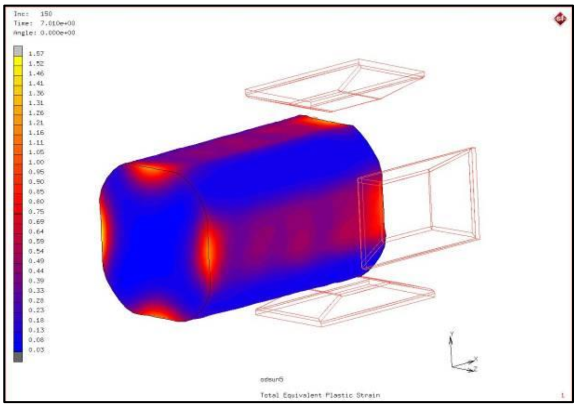

Figure 4 After the first 8-edge passage

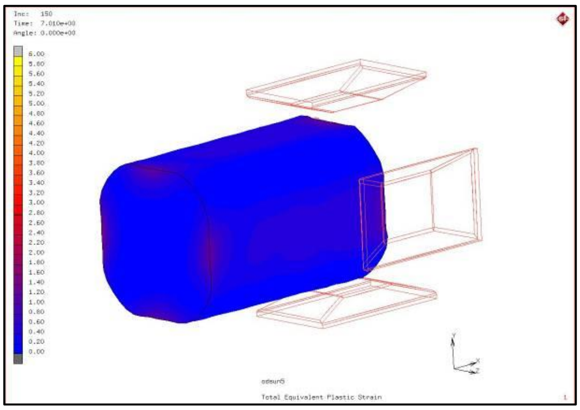

Figure 5 After the second 8-edge passage

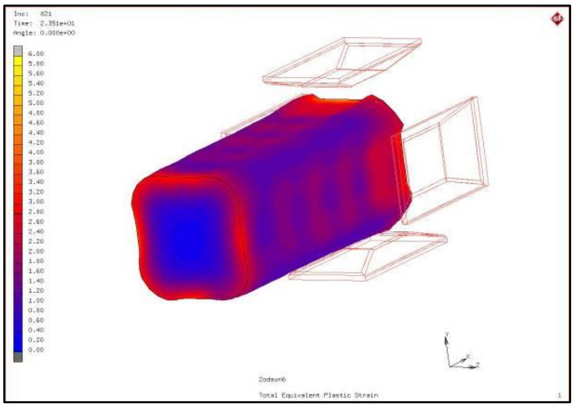

Figure 6 After the third 8-edge passage

All simulation images are shown with a so-called „Total Equivalent Plastic Strain". It is assumed that the entire cross-section of the forged bar will be sufficiently formed with a positive ultrasound check, assuming the standard internal quality of the starting ingot, if the total deformation is around 2 and higher. Laser aiming starts from the fourth pass until the final completion [4].

5 Conclusions

This new technology can guarantee sufficient forging when forging bars with diameters smaller than approx. D360 mm. However, to achieve deformation resistance, it is not possible to prevent deformation of the anvils, so it is recommended to install laser aiming on the RKS to ensure accurate bar dimensions during forging.

The use of a laser camera will allow the operator of the high-speed forging machine to more effectively control the intermediate dimensions of the forging. Before the introduction of this technology, it was necessary to check the wear of anvils using gauges, now the operator has this information in real time.

The reference list

[1] DEGARMO, E. P., BLACK, J. T.; KOHSER, R.A.: *Materials and Processes in Manufacturing*, 11th ed., Wiley, 2011.

[2] TALER, J., DUDA, P.: *Solving Direct and Inverse Heat Conduction Problems.* Berlin, 2006.

[3] LIENHARD, J.H.: *A heat transfer textbook*. 3 rd edition. Cambridge, Mass: Phlogiston Press, 2008.

[4] SHIH, T.-M.: *Numerical Heat Transfer.* Series in Computational Methods in Mechanics and Thermal Sciences. Washington: Hemisphere Publ. Corp., 1984.

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Design of Sensible Heat Storage Tank for Education

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Keywords: Thermal energy, Thermal energy storage, Heat storage tank, Student education

Abstract: Thermal energy and its need for humans will always be a serious issue. We come into contact with heat anywhere. From warming yourself by the fireplace, to taking a nice bath in warm water. Sufficient heat needs to be provided for all areas of society. Using thermal energy storage makes sense for heat sources that cannot deliver the required amount of heat in a short period of time. To ensure that there is always enough heat, the efficiency of heat-handling equipment needs to be improved. This requires a sufficient number of experts to further develop the domain of heat accumulation. Students' education in this domain through laboratory exercises is the proper step. Students acquire theoretical knowledge and practical skills. At the same time, they test the efficiency of heat storage and look for innovation in this domain. It will be achieved specifically, by designing a heat storage tank teaching model in various designs from the perspective of material construction, heat bearing medium and by changing other parameters of the storage tank or measuring environment. They also compare computer simulations to see what effect the direction of flow of the heat transfer medium has on the functionality of the heat storage device. By subsequently measuring and processing the collected data, students can determine the effectiveness of individual designs of this heat storage device learning model. They can then use the acquired knowledge and practical skills in practice.

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1 Introduction

The world's need for heat will always be higher than it is currently. By raising people's living standards, other factors will also increase. For example, higher energy consumption. Appropriate solutions must therefore be found in each domain separately. Heat energy is certainly one of those domains. Burning fossil fuels generate the necessary amount of heat in a short time. However, green energy trends call for new solutions. Sustainable development also demands that sufficient resources, which have to be preserved for future generations. This puts the use of waste heat, thermal energy from renewable sources and the use of excess heat during the summer period at the forefront. From the perspective of large amount of heat generated over a short period of time, these alternative energy sources are not yet able to match the burning of fossil fuels. Their potential is that they offer themselves to us for free in a long run. In this case, thermal energy storage is the most appropriate usage. The amount of heat accumulated depends on the performance of the reservoir. Nowadays there do exist stable heat storage tanks, which are using sensible heat. Another group is latent heat storage tanks, where the state of the working substance changes. The last group are thermochemical heat storage tanks. In practice, the most common uses are for sensible heat storage tanks, but their efficiency rating is not very high. One example is the accumulation of thermal energy into the earth's wells, where only 10-20% of the energy which had been delivered to this reservoir is being used. This creates the need to look for new innovations in thermal energy storage [1,2,12]. It follows that there also needs to be enough educated people in the area to address this issue. So, educating new experts in heat storage is just as important as finding innovation in this domain.

2 Heat stroage tank using the sensible heat of solids

The heat storage tank accumulates or stores excess heat until this heat energy is consumed. Heat energy accumulation makes sense even when the heat source is not enough to supply the necessary amount of heat to the circulation. Such peaks may be covered by a more efficient heat source, or just by a pre-prepared heat storage tank [3]. Heat storage tanks using appreciable heat operate on the principle that heat is stored in the material by raising its temperature, without the material changing state. Both solids and liquids are used in the sensible heat storage tanks. The amount of heat accumulated depends on the material used inside the storage tank [2].

Table 1 Thermal properties of materials using sensible heat [4]

Material	Density [$g.cm^{-3}$]	Thermal conductivity at 20 °C [$W.m^{-1}.K^{-1}$]	Specific heat at 20 °C [$J.kg^{-1}.K^{-1}$]	Thermal diffusivity [$m^2.s^{-1}$]
Water	1.0	0.6	4187	$1.433 .10^{-7}$
Basalt	2.3–3.0	1.2–2.3	700–1230	$6.843 .10^{-7}$
Slag	2.7	0.6	840	$2.646 .10^{-7}$
Andesite	2.6–2.7	2.3–2.8	815	$11.807 .10^{-7}$
Dolomite	2.8	2.1	802	$9.352 .10^{-7}$
Concrete	2.2–2.7	0.9–2.0	750–1130	$6.296 .10^{-7}$
Steel Slag	3.0	2.0–3.5	996	$9.489 .10^{-7}$
Aluminum	2.7	204.0–238.4	896–945	$890.015 .10^{-7}$
Brick	1.7–1.8	0.5–0.7	840	$4.082 .10^{-7}$
Steel	7.8	40.0–50.0	571–600	$98.535 .10^{-7}$
Copper	8.3–9.0	372.0–385.0	383–419	$1091.203 .10^{-7}$

Table 1 shows the thermal properties of water, rock and building or industrial materials. Based on this data, it is clear that water has a better specific heat capacity than solids. Still, it makes sense to use these materials for heat accumulation. The main reason is that they can reach higher temperatures than water. The water boils at 100°C and as the temperature rises further it begins to change its state from liquid to steam [1]. In addition to capacity, thermal diffusivity, which describes the rate at which heat spreads [5], is also an important parameter. In this case, they lead copper with aluminum. Water has the least thermal diffusivity from these materials.

2.1 Sensible heat storage in practice

The use of solid particles to accumulate heat can also be observed in practice. The most common type of appreciable heat reservoir are water reservoirs. The container shell uses materials that are not corrosive in contact with water, such as carbon steel, concrete or plastics. Thermal insulation is used to eliminate heat loss through the container casing [1,12].

Gravel heat storages are also used. Their advantage is the ability to reach high temperatures and they have good mechanical resistance. They are mainly installed in the ground and must be insulated to prevent heat from leaking into the surrounding area [1,2].

One of use is to charge the Earth's surface using a heat pump. During the summer period there is excess heat in most buildings, which causes a feeling of heat discomfort [6]. This excess heat energy is extracted from the building using a heat pump and stored in the earth's wells, where some of it can be preserved until it is used for heating. These wells are 4 -10 meters apart and contain a U-shaped pipe in which heat transfer fluid flows. The medium temperature at the inlet is 70°C and 40°C in the heat storage. The efficiency of this reservoir is 10-20% and has a longer rise time [1,7].

Another way to use solid particles to accumulate heat is to use them in a steam sauna. Heat the stones to a temperature higher than the boiling point temperature of the water. If water is poured on these stones, it takes away the heat stored in them and changes the state of the water from liquid to steam. In this case, the water is already subject to latent heat, but the stones continue to work with sensible heat [8].

3 Design of heat storage tank for education

The thermal energy storage device must meet certain conditions. It shall have sufficient insulating properties to maintain the heat in the reservoir for as long as possible and in the same time, it has to avoid unnecessary losses. This role will mainly be provided by thermal insulation, which will be placed over the entire surface of the container. Thermal insulation parameters are determined by basis of heat losses. Another feature needed is leakage, the device must not overflow. It must also be strong enough not to damage solid particle filling [1,10].

As this is a model designed mainly for education, it´s dimensions may not be large. The main stack has been selected catalog-based from available sources. It is a PVC component of a drainpipe which, when other components are added, will form a 12 liters heat storage tank. All components are shown in the drawing shown at figure1.

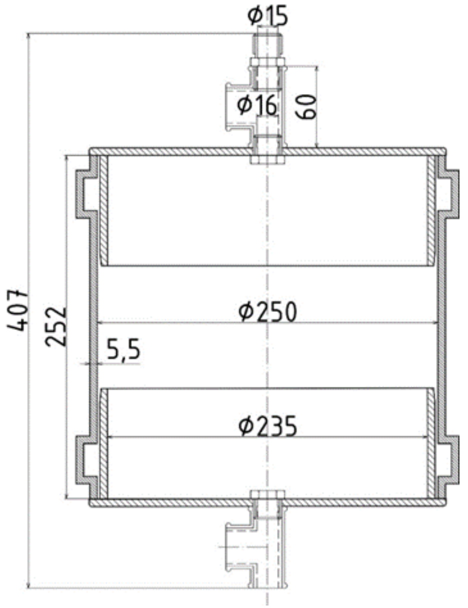

Figure 1 Parameters of heat storage tank

The heat storage tank is designed in two designs. In the first case, the heat transfer fluid inlet is on the top of the storage tank and in the second case on the bottom of the tank. A comparison of two designs is being described from the perspective of heat transfer flow kinetics in the following chapters. In both cases it is a standing storage tank. This allows the thermal medium to circulate all the solid particles that are placed in this reservoir.

Also, tank monitoring takes place for both designs using 5 thermocouples, of which 3 thermocouples are located inside the tank at the inlet, center of the storage tank and at the outlet. Another thermocouple is located on the surface of the container and the location of the 5th thermocouple is on the surface of the thermal insulation. One more thermocouple is used in the measurement, but this temperature sensor is not in direct contact with the reservoir, its task is to measure the ambient temperature to determine heat loss [9].

Figure 2 and figure 3 show the design of the heat storage tank, which differs from a design standpoint by the use of a vent valve at first design. The direction of the heat-bearing medium inlet is also different. The location of the thermocouples, which is the same for both designs, is also shown.

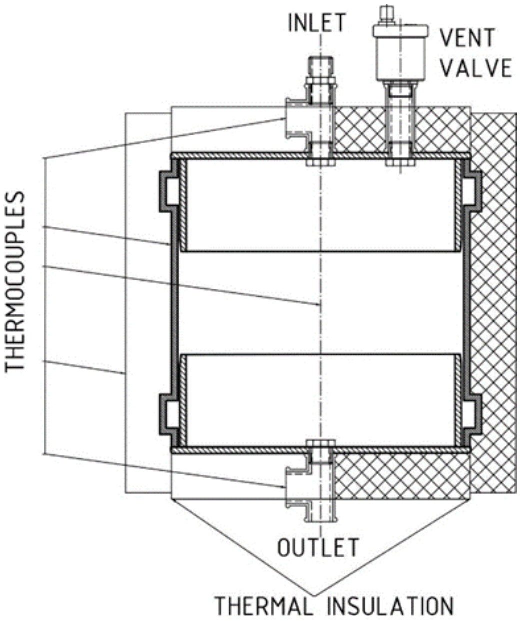

Figure 2 Heat storage - design 1

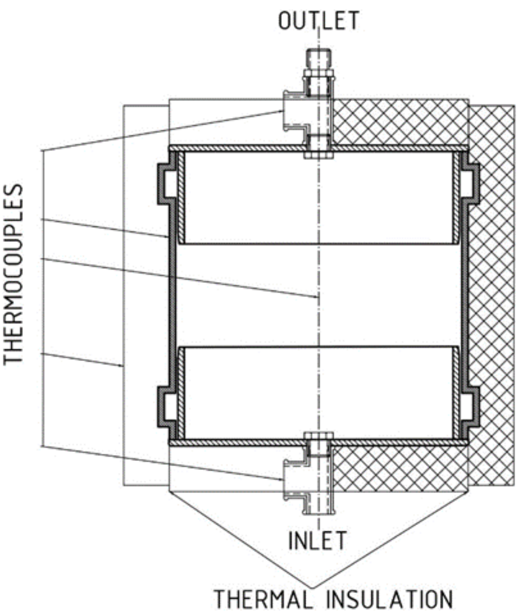

Figure 3 Heat storage - design 2

For this design, the direction of flow of the heat transfer medium is in the same direction as the gravitational force. The gravitational force does not affect the intake pipes, and that does not need any specific properties. However, the problem is the air, which is sticking to the top of the stack. To remove it, a vent valve has been added to release all the air out of the container.

For the second design, the direction of flow of the heat transfer medium is from the bottom. Because of this, they have to overcome the hydrostatic pressure caused by the force of gravity. If the valve on the intake had a weaker leak, it could leak. However, the advantage of this is that all of the air from the reservoir flows in the direction of the heat transfer medium and the result of this can be seen in no supplementary need to install any additional components, as was the case with the first design.

4 Computer simulations of heat transfer medium flow

After comparing these two types of designs from a structural perspective, the comparison also follows from a thermal perspective. Specifically, the influence of the direction of flow of the heat transfer medium on the temperature distribution in the heat storage tank is investigated. This comparison is made by using computer simulations. In this case, was created a 60 minutes simulation. Of which, 30 minutes for heating material and 30 minutes for taking heat from the material.

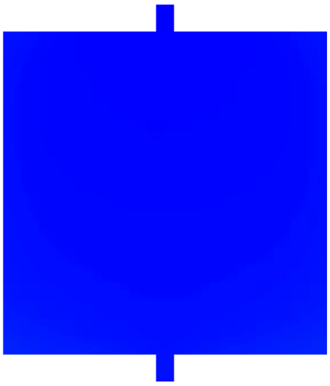

Figure 4 Minimum temperature in tank

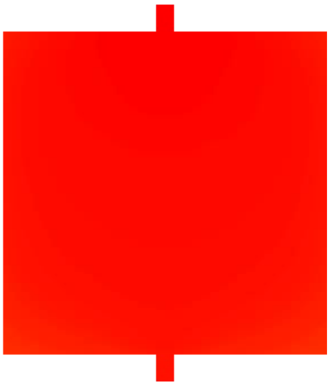

Figure 5 Maximum temperature in tank

Figure 4 shows the state of the simulation at its minimum temperature. For both designs, this state is the initial state and this state also ends the entire measurement. Figure 5 shows the simulation state after heating, when the heat storage tank reaches its maximum temperature.

Figure 6 and figure 7 represent the state acquired by the simulation after 2 minutes of heating respectively from the beginning of the entire measurement.

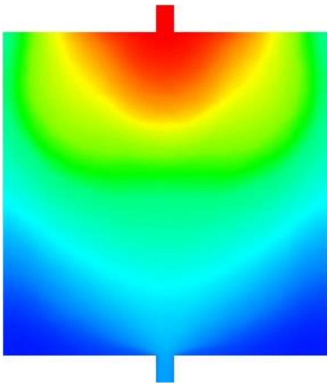

Figure 6 Design 1 heating

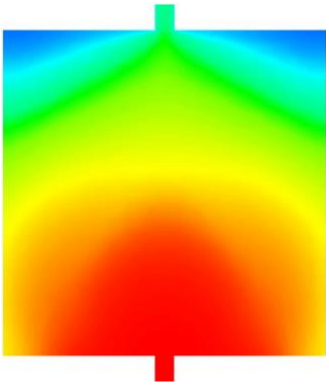

Figure 7 Design 2 heating

The maximum temperature in the entire storage tank for first design was reached within 15.33 minutes of the start of the measurement.

Figure 8 and Figure 9 show the state of the simulation after 2 minutes of cooling respectively after 32 minutes the beginning of the entire measurement.

When we heated the second design, the entire reservoir reached its maximum temperature in 9.17 minutes from the start of the measurement.

At first design shown on figure 8, the entire volume of the storage tank was cooled in 15,33 minutes from the start of cooling, in total of 45,33 minutes from the start of the measurement.

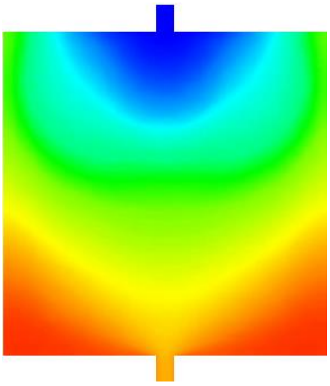

Figure 8 Design 1 cooling

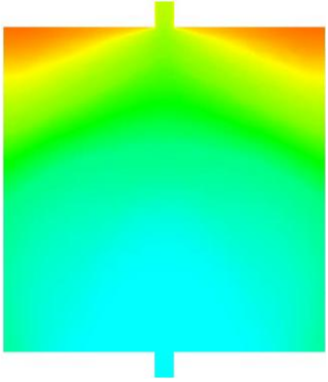

Figure 9 Design 2 cooling

For Figure 9, the material in the entire reservoir reached a minimum temperature of 9.17 minutes from the start of cooling, or 39.17 minutes from the start of measurement.

From simulations, it was found, that changing the direction of flow altered the heating time or cooling of the container. The heating and cooling times were shorter when inlet of heat transfer medium was from above (carry-over 2). For the Type 1, the magazine had more inertia. However, in both cases the maximum temperature was reached throughout the stack. It follows that the direction of flow of the heat transfer medium does not affect the temperature distribution in the heat storage tank.

5 Measurement

Prior to measurement, necessary requirements need to be determined and further differentiated, which variables or parameters must be stable, and which may be variables. These conditions shall then be maintained throughout all measurements. If the same requirements were not observed for individual measurements and the number of variables varied, then comparing these measurements would not be objective and evaluation would not be possible [9,13].

Stable/variable measurement conditions:
• material type
• amount of material in the tank
• grain of material
• type of heat transfer medium
• heat transfer flow
• heat transfer medium temperature at inlet
• heat transfer medium temperature inside the reservoir
• ambient temperature
• thermal insulation type
• thermal insulation thickness
• number and location of temperature sensors
• measurement duration

For this measurement, the variables are the material type, the temperature inside the storage tank and also the measurement duration. The rest of the presented variables, which were mentioned have stable values. During measurements, the amount of heat sold to the material in the container through the heat transfer medium must be determined. For this reason, the temperature in the heat storage tank needs to be measured. This role is performed by the temperature sensors which are distributed in the heat storage tank according to the drawing [9]. The thermocouple at the inlet measures the temperature of the heat transfer medium entering the reservoir at a constant temperature. Thereafter, the time taken for the thermocouple to measure the same temperature value at the outlet as at the inlet is monitored. It is assumed, that if the inlet and outlet temperatures have the same temperature or minimum difference, then the material in the container has already reached that temperature value as well. This means that the material has already received the maximum amount of heat from the heat transfer medium at this temperature. The thermocouple has also been added to the center of the stack. This allows the stack to be divided into 2 zones and their progress monitored to obtain more accurate data. Temperature sensors on the heat storage tank surface, insulation surface and thermocouple are used to measure ambient temperature to determine heat loss.

6 Measurement Evaluation

After the measurements, the temperature values and time lengths of each measurement are known. However, in order to determine the amount of accumulated and later transferred heat, these data are still inserted into the formulae and a calculation is made. The results from the calculations are compared and then evaluated. Since the main part of this laboratory exercise is educating students on thermal energy accumulation, this area is also being evaluated.

6.1 Heat balance

The thermal balance equation is constructed from the calorimetric equation of the heat transfer medium on the thermal energy supply side. And because devices can't operate at 100% efficiency, on the side of the transferred heat is the sum of the calorimetric equation of the material in the heat storage tank and the heat loss caused by heat leakage through the walls of the storage tank [1,11].

$$Q = m_{H2O} \,.\, (c_{p,H2O,1} \,.\, t_{H2O,1} - c_{p,H2O,2} \,.\, t_{H2O,2}) \,.\, \tau = m_{mat} \,.\, c_{mat} \,.\, (t_{mat2} - t_{mat1}) + Q_{ST} \;\; [J] \quad (1)$$

m_{H2O} – mass flow of water, [kg. s^{-1}]
$c_{p,H2O}$ – specific heat capacity of water, [J. kg^{-1}. K^{-1}]
$t_{H2O,1}$ – water temperature at the beginning of the measurement, [°C]
$t_{H2O,2}$ – water temperature at the end of the measurement, [°C]
τ – measurement duration, [s]
m_{mat} – mass of used material, [kg]
c_{mat} – specific heat capacity of material, [J. kg^{-1}. K^{-1}]
t_{mat1} – material temperature at the beginning of the measurement, [°C]
t_{mat2} – material temperature at the end of the measurement, [°C]
Q_{ST} – heat loss, [J]

6.2 Heat loss

Heat loss can be defined as the leakage of heat from the device to the surrounding area without fulfilling its original purpose. Thermal insulation is used to reduce heat loss [3].

$$Q_k = \alpha_k \,.\, A \,.\, (t_1 - t_2) \; [W] \qquad [10] \qquad (2)$$

α_k – thermal conductivity, [W. m^{-2}. K^{-1}]
A – area, [m^2]
t_1 – temperature on surface of tank, [°C]
t_2 – temperature of ambient, [°C]

$$Q_{ST} = Q_k . \tau \quad [J] \qquad (3)$$

6.3 The Benefits of Laboratory Exercise for Students

- Acquiring new knowledge on thermal energy storage
- Heat storage device model design
- Current simulation - comparing multiple models
- Experimental measurements
- Calculations with measurement substitution
- Measurement evaluation - practical comparison

7 Conclusion

The society will always need a supply of heat or cold. Heat accumulation should have a large presence in this domain. It is equally necessary to have people, who are experienced enough to look after this domain. During these laboratory exercises, the students went through a process of acquiring theoretical knowledge of heat storage. Subsequently, by designing a heat storage device teaching model, comparing computer simulations, measurements up to evaluating the effectiveness of individual heat storage device designs. It is hoped that this experience will help them to address this issue in practice, and thus contribute to innovation in this domain.

The reference list

[1] KABRHEL, M.: *Akumulace tepla / Thermal Energy Storage*, České Vysoké Učení Technické v Praze, 2011.

[2] ELOUALI, A., KOUSKSOU, T., EL RHAFIKI, T., HAMDAOUI, S., MAHDAOUI, M., ALLOUHI, A., ZERAOULI, Y.: Physical models for packed bed: Sensible heat storage systems. *Journal of Energy Storage*, Vol.23, pp.69-78, 2019.

[3] Javys, a.s. *Energetický slovník* [online]. Available: https://www.javys.sk/sk/informacny-servis/energeticky-slovnik/ [16 December 2021].

[4] TISKATINE, R., OADDI, R., EL CADI, R. A., BAZGAOU, A., BOUIRDEN, L., AHAROUNE, A., IHLAL, A.: Suitability and characteristics of rocks for sensible heat storage in CSP plants. *Solar Energy Materials and Solar Cells*, Vol.169, pp.245-257, 2017.

[5] VOSTEEN, H. D., SCHELLSCHMIDT, R.: Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rock. *Physics and Chemistry of the Earth, Parts A/B/C*, Vol.28, No.9-11, pp.499-509, 2003.

[6] OKE, T. R.: The urban energy balance. *Progress in Physical geography*, Vol.12, No.4, pp.471-508, 1988.

[7] RAAB, S., HEIDEMANN, W., MANGOLD, D., MÜLLER-STEINHAGEN, H.: Solar assisted district heating system with seasonal hot water heat store in Friedrichshafen (Germany), 2004.

[8] LAUKKANEN, T., KHAN, H., ZACCARDI, F., LAUKKANEN, J. A.: Association between sauna bathing and fatal cardiovascular and all-cause mortality events. *JAMA internal medicine*, Vol.175, No.4, pp.542-548, 2015.

[9] CHILDS, P. R., GREENWOOD, J. R., LONG, C. A.: Review of temperature measurement. *Review of scientific instruments*, Vol.71, No.8, pp.2959-2978, 2000.

[10] LENHARD, R., KADUCHOVÁ, K., ĎURČANSKÝ, P., HEJČÍK, J.: *Výmenníky tepla*, Žilina, Equlibria, 2020.

[11] VITÁZEK, I. *Teplotechnika a hydrotechnika*. SPU v Nitre. Nitra, 2012.

[12] RIMÁR, M., FEDÁK, M., VÁHOVSKÝ, J., KULIKOV, A., ORAVEC, P., KULIKOVA, O., ŠMAJDA, M., KÁŇA, M., Performance Evaluation of Elimination of Stagnation of Solar

Thermal Systems. *Processes*, Vol.8, No..5, pp. 1-21, 2020

[13] VARINY, M., BLAHUSIAK, M., JANOSOVSKY, J., HRUSKA, M., MIERKA, O.: Optimization study on a modern regeneration boiler cold end operation and its feedwater system integration into energy system of a paper mill. *Energy efficiency*, Vol.12, No.6, pp.1595-1617, 2019

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