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Authors: Konrad Rojcewicz, Zbigniew Oksiuta

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VIABILITY ANALYSIS OF PINE SAWDUST DRYING IN A FOUNTAIN DRYER

Konrad ROJCEWICZ*, Zbigniew OKSIUTA*

Faculty of Mechanical Engineering
Bialystok University of Technology
Wiejska 45C street, 15-351 Bialystok, Poland

krojewicz@gmail.com,

Abstract: The article presents an analysis of the physicochemical properties of pine sawdust originating from the area of the Knyszyńska Forest, in the context of the possibility of their drying in a fountain dryer. A number of tests were carried out on dry pine sawdust of 45% moisture, such as chemical composition, calorific value, ash content as well as morphological changes of wet and dried material. The water storage mechanism in chips and the mechanism of formation of a fountain bed were also discussed. Based on the obtained results, several technical solutions and modifications of the fountain dryer were proposed. These modifications enable the sawdust of heterogeneous size and shape to be dried in a fountain dryer as well as additional functional properties.

Key words: sawdust, fountain dryer, fountain bed, conical spouted bed, pellets, sieving analysis, BET method

1. INTRODUCTION

Forest and agricultural materials are used for the production of fuel biomass. In the case of biomass from the forest, one can get sawdust with different morphology (size and shape), moisture content, and physicochemical properties. The problem is also the content of solid impurities and the elemental composition, e.g. the content of chlorine, which during combustion emits dioxins which are hazardous to health. The raw material in the form of sawmill chips can be processed into a specific final product, e.g. pellets. The process involves chip thickening under the action of external and internal forces applied, in order to obtain a fixed shape, and size of the pellet. Before the granulation, the chips must have adequate humidity, calorific value, color, purity (free from such contaminants as bark, large pieces of wood, stones, or pieces of metal), as well as low ash content.

Drum and belt dryers are often used for drying sawdust. Each dryer for structural reasons has its limitations and disadvantages e.g. their efficiency or usage exhaust gases for drying materials (Witrowa-Raichter, 2009; Strumillo C., 1983). Drying with exhaust gases causes color changes of sawdust, their demineralization, and higher ash content, which adversely affects the pelleting process (Dan Bergströma, 2008). This problem can be solved by drying sawdust with a hot air stream.

Fountain dryers with a vertical drying chamber allow the material to be dried in a very efficient way and dispersing the material by creating the fountain effect. Also, the scattered, detached material can be dried with hot air instead of exhaust gases. However, fountain dryers are mainly used for drying granular materials of equal size and weight, e.g. cereal grains. Hence, during drying sawdust in a typical fountain dryer, there is a number of process difficulties, in particular the formation of slugging effect, limiting the amount of dried material.

The main aim of this work is analysis of possibility of using a fountain dryer in order to drying of pine sawdust for pellets production. The paper presents the results of research work on selected physicochemical properties of pine
shavings obtained from various sawmills in Knyszynska forest, and proposition of improvement of fountain dryer for drying wet sawdust.

2. MATERIAL AND METHODS

Two measurements presented in this article relates with the fountain drying process, namely: the stand for testing the flow of loose materials and the sawdust drying process characterization (drying curves). Rest of the measurements, tests, refer to the sawdust material. The tested sawdust was collected from various pine trees, i.e. from wood that was fresh, rotten, and exposed for a long time for different weather conditions. Trees were also cut at different seasons. In the case of pellet production, a large amount of sawdust is needed. Therefore, the authors in this work wanted to open up the real conditions encountered in the case of granulate production.

2.1. Sawdust material

Sawdust resulting from the machining of wood have the shape and size mainly dependent on the cutting tools, process parameters, and the physicochemical properties of a wood. In general, a chip morphology is mainly dependent on the type of machining tool used, which an example is presented in Fig. 1. Due to a high availability, a pine sawdust obtained from a band sawmill was chosen for this study (Fig. 1a).

Figs 1b and 1c show chip morphology obtained using a frame sawmill and a wood milling machine, respectively.

Due to an increased tooth size in the frame sawmill and the reciprocating movement of the tool, these chips are much larger compared to the chips obtained from a band sawmill. Such sawdust have the shape of sticks of varying lengths. Whereas the shape of the chips obtained on the wood milling machine is defined by the geometry of the milling cutter and they are thick and twisted.

2.2. Sawdust testing methods

A representative sample of pine sawdust from a band sawmill (Fig. 1a) with a mass of 10 kg and an average moisture content of 46±2% was collected and secured. The chips were sealed in hermetic containers and then used for further testing of their properties. In order to determine the morphology and selected physicochemical properties of the pine sawdust, the following tests and observations were carried out:
• calorific value, using a caloric bomb (Parr 6100);
• ash content, by burning samples in the oven (Nabertherm P330);
• microscopic observations, by means of SEM equipped with the EDS device (Hitachi 3000N) and optical microscope (Olympus 2000);
• chip specific surface area, the BET method;
• sawdust drying process (for establish drying curves as a function of temperature), using a dryer (Radwag MA 50R);
• size distribution of wet sawdust and after drying, using the ImageJ program;
In addition, sawdust was fed to various thermal treatments, in a thermal furnace and in a drum dryer at 400 °C, where the drying agent was exhaust gas. A selected sample of 0.4 kg was used to determine the calorific value of pine sawdust. The sawdust sample was placed on trays and dried until the mass stabilized. The mass of the sample was measured every 1 h. Then, after stabilization, moisture was measured using a moisture analyzer, which was 8.2± 0.1%. Further, 15 representative specimens with weight about 0.01 kg were selected again, which were ground in a small mill from kit and pressed into a pellet with a diameter of 20 mm and a height of about 14 mm. The specimens were precisely weighted, and then tested with a calorimetric bomb (Parr 6100). The operating parameters of the calorimetric bomb are given: oxygen for combustion - \( \text{O}_2 = 99.95\% \); working pressure - \( P = 30 \text{ bar} \); weight of separated water - \( m_w = 2 \text{ kg} \).

For the ash content testing, 30 samples of dried sawdust, with 0.5% of humidity and 0.001 kg mass were used for a single sample. Sawdust samples were placed in pre-weighed crucibles. The crucibles were placed in a laboratory oven (Nabertherm P330) and allowed to burn. After cooling, the samples were weighed with a laboratory balance with accuracy of 0,001×10^-3 kg. The ash content was determined indirectly using formula (1).

\[
A = \frac{m_3-m_1}{m_2-m_1} \times 100\%_{\text{max}} \quad (1)
\]

where:

\(A\) - is the content of volatiles in the analytical sample [%_{\text{max}}],
\(m_1\) - is the mass of the crucible,
\(m_2\) - is the mass of the crucible with the raw material being burnt,
\(m_3\) - the mass of crucible with ashes.

Scanning electron microscope (SEM) and optical microscope (OM) were used to study the microstructure of both wets and dry sawdust samples. Samples of varying humidity from 5% to 46% were observed. Due to the scattering of light in the water contained in the samples during OM observations, to increase the contrast of the chips, they were dyed blue with ink. Also, the examinations of the specific surface area of the sawdust by means of the BET method was performed. The sample of sawdust was inserted into a chamber with nitrogen penetrating the surface of the material. Knowing the pressure, temperature and gas volume one can calculate how much gas has been absorbed on the chip surface based on the mass difference. Using the formula (2), the specific surface area of the wet and dry sawdust was calculated.

\[
S_p' = a_p \times N \times w_p \quad (2)
\]

where:

\(N\) - the Avogadro’s number,
\(w_p\) - the surface occupied by a particle in the surface of the test sample,
\(a_p\) - the amount of the gas absorbed.

Three humid (46% of moisture) samples of 0.01 kg each were used for the sawdust drying tests, to dried them for 5±2%. For the analysis of phenomena occurring during the drying process of sawdust, so-called drying curves were used, as a function of drying time and temperature. A moisture analyzer (AGS200) was applied for the tests. The tests were carried out for three temperatures 100, 125 and 150 °C, repeating each of them three times.

Measuring the size of sawdust, using computer image analysis method, the change in the equivalent diameter of chips before and after drying was determined. An example image of the sawdust before drying and after drying is presented in Fig. 2. Series of sawdust images were taken. Then the best quality photos were selected, scaling, converted, and automatically analyzed by the computer program (ImageJ). 500 wet chips and 500 dry chips were analyzed.
Observations of sawdust motion kinematics in the fountain stand (Fig. 3) were performed. This study was intended to visualize and analyze the processes occurring in the fountain bed. The fountain test stand (Fig. 3) consists of a glass pipe 1 through which air was pumped at a given speed by a fan 6, controlled by means of an inverter and a throttle valve 5. The amount of air flow was measured by the rotameter 3, so it was possible to precisely set the flow. The single test duration was 10 minutes. The entire fountain process was recorded with camera 4.

Samples with three different humidity (46%, 37%, 28%) were prepared for the testing. In the first phase, a flow rate of 600 dm$^3$/h was established for sawdust volume of 100 ml. The parameters of the stand are presented below: testing time - $t_1=10$ min.; flow rate - $S=600$ dm$^3$/h; sample volume - $V=100$ ml; air temperature - $t_2=22.5$ °C; air humidity - $Y_p=50$ %. Sawdust moisture before drying: $Y_1=46\%$, $Y_2=37\%$, $Y_3=28\%$. Sawdust moisture after drying: $Y_1'=22\%$, $Y_2'=7\%$, $Y_3'=5\%$.

The sieving analysis of chips with different humidity was also carried out using the Multiserw LPzE-2e laboratory shaker. Sieves were set up in accordance with PN-EN-ISO 3310. Three of 0.01 kg of samples each obtained after drying in the fountain bed were used.

3. RESULTS AND DISCUSSION
3.1 Calorific value

The calorific value for the dried pine chips was 18.07 MJ/kg, which is similar to the data described in the literature (Gao Ningboa, 2015). By means of low vacuum SEM-EDS analysis, chemical composition of the pine chips were detected. The pine sawdust consist of: C-53.9%; O-40.1%; K-0.01%; S-0.005%; Cl-0.005%. Similar chemical composition was reported in the literature (Małgorzata Kajda-Szcześniak, 2013). Slightly different composition obtained from other regions of Europe (Helder Filipe dos Santos Viana, 2018).

3.2 Ash content

The average ash content after drying the sample in the stand presented in Fig. 3 is 0.504±0.15. This is a similar amount of the ash obtained by other authors (Longin Glijer, 2011; Jirjis R., 1995; A. Bryś, 2016). Ash content was also tested for dried sawdust in a conventional drum dryer, where the drying medium is exhaust gases. The ash content was 0.743±0.12 (Fig. 4).

![Fig. 4. Ash content depending on the method of drying with dried air and exhaust fumes.](image)

It can be noted that the ash content in sample dried in exhaust gases is 25% higher compared to sawdust dried in a fountain bed. This is due to the fact that the exhaust gases contain ash particles that settle on the surface of the wood chip. Note, that the pine samples used for this comparative tests were taken from an industrial drum dryer, which was equipped with firewalls with settling chambers for particle separation from the exhaust gases.

The percentage of ash content essentially affects the quality of the raw material. During the production of fuel pellets, the amount of hard ash particles should be as low as possible. Too much of them can lead to clogging of furnace burners in which solid fuel in the form of granules is burned.

Additionally, ash settling on the chip surface causes a color change to darker pellets, which is not desired by customers and results in a lower price of the product. Therefore, it is proposed to hot air drying as opposed to exhaust gases.

3.3 Microscopic observations

In order to determine the water retention in the chips and the processes that occur during their drying, a number of microscopic observations of the samples were carried out. Literature reports (Strumiłło C., 2006; Kudra T.; Arun S. Mujumdar, 2009, Patrick Perre; Roger Brian Keey, 2006) show that the water in the wet material is located inside the growth cells, on the surface and between the wood chips.

Microscopic observations show that the water contained inside the wood's cells (capillary 1, Fig. 5a) can lead to changes in chip morphology as a result of intensive drying. This phenomenon is observed during rapid heating of a small pieces of sawdust.
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Fig. 5 (a) Chip structure, 1-capillary (dry sawdust). (b) Channel permeability in a chip (dry). (c) SEM image of a surface of a single pine chip (dry sawdust).

Capillaries in a tree form channels where water and nutrients are transported. Depending on the degree of humidity, these channels may be partially filled with water or air (Figs. 6a and 6b). During drying process, a rapid increase in gas pressure in the ducts can cause cracking (tearing) of chips, which leads to an increase in amount of a small fraction. This process is desirable for the pellets production, because more small fractions result in better granules quality (Dan Bergströma 2008).

Fig. 6. (a) Schematic view of the water in the wet chip. 1-capillary, 2-air bubble, 3-cell walls of wet chip. (b) OM image of a wet chip filled with water and air bubbles (magnification x50, description in the text).

In Fig. 6b, the light areas (1) show air bubbles inside the cells, while the dark ones are a colored water (3). The number (2) indicates the interface between water and air. Microstructure observations confirmed that the water inside the wood chip not completely fill the internal cells.

The temperature gradient on the chip, as a result of drying, can causes internal stress, due to different thermal expansion of the chip. This causes chip twisting (warping) and wood shrinkage, which results in its structure changes during drying. This shrinkage is the greatest along the capillaries. So the shrinkage will be different depending the location of the tree trunk from which the chip comes, and the way how it is obtained.

In addition, the chips resulting from the cutting have channels with various levels of permeability (Fig. 5b) that makes it difficult to remove the water remaining from inside the crushed tubes. This also leads to the process of chips cracking described above. Also, water on the chip surface is a significant reservoir that must be evaporated in the process of drying. Due to the highly developed specific surface area, numerous capillarity’s and cavities, the chips accumulate water drops on the top layers. In the case of a lower humidity, water does not fill the entire surface tightly, but stays in the form of drops embedded in the insets. Water also occurs in a general mass of sawdust between individual particles of chips (Figs. 7a and 7b), which can be much more humid than the rest of the material. This water can get into the sawdust during rainfall or high humidity. Sawdust at high humidity stick together forming large agglomerations.

While the process of evaporation of this water from the chip surface is fast (Longin Glijer, 2011), too long time of
expose of sawdust in a high humidity conditions causes water to enter them. This is because the size of a single H₂O molecule is 0.28 nm (Pang Xiao-feng, 2014) and therefore it may easily penetrate the chips.

![Figure 7](image)

**Fig. 7.** (a) Drawing showing water accumulation between chips: 1 – water bridges, 2 – chip (wet sawdust). (b) Water between the chips forms agglomerates (wet sawdust).

### 3.4 Specific surface area

The specific surface area of the sawdust measured for the dry sample, with 5±2% of humidity, and for the wet sample, with 46±2% of humidity, is 0.5233 [m²/g] and 0.5826 [m²/g], respectively.

Analyzing these results, one can conclude that the dry sample has by about 10% a smaller specific surface area compared to the wet one. This is caused by the shrinking of wood, due to the evaporation of water, which during the drying process leaves the cells and thereby reduces their size. The shrinkage of wood depends on the fiber direction, e.g. wood shrinks 1.7 times less in the radial direction and this is 20 times less in the longitudinal direction than tangential direction. It should be mentioned here that this phenomenon occurs for sawdust of 30% and lower humidity, as it is reported in (Longin Glijer, 2011; Patrick Perre; Roger Brian Keey, 2006).

### 3.5 Determination of chip drying characteristics

The drying process of chips with a humidity of 46% as a function of time and temperature is presented in Fig. 8. In the drying process, three characteristic stages can be distinguished.

Stage 1 is the period in which the heated chips have negligible weight loss. This stage includes the ranges: T₁, T₂, T₃, and for three temperatures, which are equal in time, last about 60 seconds and do not depend on the temperature.

Stage 2 with ranges of T₂₁, T₂₂, T₂₃ are of different length (time axis) and depend on the drying temperature. The T₂₁ section at 150 °C is the shortest and lasts about 590 s. Comparing with the drying time at 100 °C, the drying time increases to 1000 s and it is 59% longer.

Stage 3 shows a plateau, where no changes in chip mass was observed. This means that the process of water evaporation has been completed and only the dry mass of sawdust remained (Strumillo C., 2006).

The drying curves show the starting parameters for the further comparative analysis of the drying process of the pine sawdust. They were made in heating conditions without air flow. Thanks to this, by comparing them with the drying curves on the test stand, we can see how other parameters, such as blowing speed, temperature, or the type of bed, affect the drying speed.

The obtained results may suggest that in a certain weather condition, it is reasonable to pre-heating the sawdust before drying. Thus, in the autumn-winter period, when the sawdust are very moist, the drying time can be significantly reduced. Pre-heating of the sawdust can be carried out outside the drying chamber, e.g. in screw feeders. The advantage of pre-heating has been confirmed by literature (Witrowa-Raichter, 2009; Keey R.B., 1991; S De la Fuente-Blanco, ERF De Sarabia, 2006; A. Bryś, 2016).
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3.6 Image analysis of sawdust before and after drying

This section presents the histogram (Fig. 9) of the dry and wet chip fractions distribution presented from images in Fig 2. From the graph, one can conclude that the highest percentage of the chip size is 0.5 mm, both wet and dry and that the total proportion of particles smaller than 0.5 mm is greater for the dry chips with 5% of moisture. This confirms the fact that during drying process, crushing and cracking of the sawdust occurs.

Analyzing the results presented in Fig. 9, it can be concluded that the average wet chip size is approximately 22% larger than dry. The average chip sizes are similar to those reported in the literature (Longin Glijer, 2011; Patrick Perre; Roger Brian Keey, 2006). Furthermore, after drying, the chips are in the range from 0.125 to 2.0 mm. Note that the large chips are undesirable, interfering with the drying process in a fountain dryer. However, they constitute only about 1% of the entire percentage of the vortices. Whereas the smallest chips constitute about 5% of the total value, and they are desirable during the granulation process. They may have a few percent higher humidity, compared to larger chips, but due to their lower weight, the water evaporates faster.
3.7 Sieving analysis

Fig. 10 presents images of the pine sawdust after sieving analysis of drying them in the fountain bed, whereas Fig. 11 presents a histogram of chip size distribution with different humidity, 45%, 37% and 28%, respectively. On the basis of the obtained results, one can stated that the data of the sieve analysis generally coincide with the results of the image analysis, where about 90% of the chips are in the range of 0.125-1.0 mm, and a chip moisture affects particle size distribution.

![Image of sawdust fractions](image.jpg)

**Fig. 10.** Sawdust fractions obtained by sieving analysis of sawdust with an initial moisture content of 37%.

![Image of chip size distribution](image1.jpg)

**Fig. 11.** Percentage distribution of wet chips after drying on the test stand.

From the Fig. 11 one can see that there is ~ 45% of 0.5 mm chips, ~ 28% of chips has 0.25 mm size, and ~ 8% of sawdust has 0.125 mm. Also, there is about 3% of the undesirable, coarse shavings fraction with an average particles size of 1, 2 and 4 mm (Fig. 10) that have bark and other impurities. High content of the bark has a bad influence on the granulation process, e.g. increasing the ash content and changing the color. Thus, a good solution is to use them for incineration in a furnace feeding a dryer.

Thus, subsequently technical solutions for the fountain dryer will be proposed that should eliminate the coarse particles from the sawdust.

3.8 Motion kinematics research in the fountain bed
Fig. 12 shows the stages of the formation of a fountain bed during the drying of the chips on the stand presented in Fig. 3. The chips with a moisture content of 46%, 37%, and 28% were used. The moisture of the chips after the drying process ranged from 5-8%. When analyzing the movement of particles (sawdust) in the fountain bed, several basic stages can be distinguished. Turning on the fan resulted in the bulging of the bed surface (so-called loosening) combined with an increase in volume (Fig. 12b). Then there is a phenomenon of a further increase in the volume of the bed (Fig. 12c). The interruption of the stream continuity and the formation of a trough inside the bed is the next stage of the process shown in Fig. 12d. The formation of a proper spouted bed and a gradual reduction in the number of chips inside the pipe are shown in Fig. 12e and 12f.

Note, that were also observed "levitating chips" (4) in Fig. 12g, which were not able to leave the drying chamber even after a long drying period. These individual chips are not involved in the fountain process and eventually fell to the bottom of the pipe.

From these observation it appears that one can distinguish the stages: the fixed, bubbling bed (Fig. 12a, 12b and 12c) and a rapid transition to a turbulent bed, followed by fast fluidization (Fig. 12e) (C. K. Gupta, D. Sathiyamoorthy 1999).

Based on the results obtained, it can be concluded that the time needed to dry the chips in the fountain bed is much shorter than when drying the chips with the moisture analyzer. During 600 seconds of fountain drying, a 0.1 kg sample of sawdust was dried to a moisture content of 5-8%, blowing the material with air of 25 °C. This is due to the fact that in the fountain bed one can deal with a flow of large volume of air in a short time, with very intensive turbulent chips mixing.

4. IMPROVEMENTS PROPOSED IN A FOUNDATION DRYER

Analyzing the process of drying chips in the fountain bed, the biggest problem discovered is the sawdust pollution and large size chips. In order to solve these problems, based on literature analysis (Arun S. Mujumdar, 2006; T. Kudra, 2004; Y. Liu, 2014; M Aziz, 2011, Zhang M 2017), and on the results of our preliminary research work, the authors proposed number of modifications and improvements in construction of a fountain dryer. Figure 13 shows a design solution for a fountain dryer to improve the drying process of heterogeneous materials, in this case of pine sawdust. Note that this type devices are usually used for drying homogeneous materials, e.g. powders, corns, etc.

The proposed device (Fig. 13) has the following modifications compared with a typical fountain dryer:
• bed adjustment valve 10;
• cone separator for removing stones, metal pieces, bark 22;
• an internal system of heating air by flue exhaust gas 27;
• water heater 24;
• ultra sounds heating generators 8.

The introduced improvements are designed to obtain a dried product with appropriate technological properties, i.e. sawdust with parameters necessary for the production of fuel pellets. The next step is to improve the thermal and functional properties of the dryer.

Fig. 13. Scheme of the proposed fountain dryer: 1-air outlet, 2-recuperator, 3-condensate outlet – dehydration, 4-exhaust outlet, 5-water heater, 6-dry sawdust tank, 7-fan, 8-ultrasonic generator, 9-raw material tank, 10-air cushion adjustment valve, 11-sawdust separator, 12-cyclone, 13-furnace, 14-water pump, 15-water inlet to extinguish (extinguishing system), 16-flowmeter, 17-thermocouple (temperature measurement at the output), 18-thermocouple (input temperature measurement), 19-water inlet for cooling the material in the screw feeder, 20-water inlet to extinguish the raw material in the screw feeder, 21-heavy debris discharge, 22-rotary sluice, 23-air outlet from the drying chamber, 24-water heater with flue gas, 25-screw conveyor, 26-external case, 27-inside case, 28-drying chamber.

5. SUMMARY

The goal of this work was to propose a new design of a fountain dryer, enabling making an optimal product for the production of pine pellets.

The article presents the analysis of the pine sawdust obtained from the Knyszyńska forest and their drying process, which is the first stage of the pellet production. The drying process in fountain dryers of heterogeneous sawdust materials is a big problem due to non-homogeneous material. Different particle sizes hinder the proper functioning of the bed. They also have impurities that also affect the operation of the bed. They cause that dry material has worse technological properties in terms of further granulation. Therefore, the fountain dryer should be equipped with the
tools and devices that can separate the least valuable big sawdust particles, metal parts, bark, stones and other impurities. Thus, the basic parameters of the sawdust were determined, i.e. the chemical composition, calorific value, surface area analysis, sieve analysis and ash content for drying process performed by exhausted gases and hot air. Analysis of ash content showed a significant reduction of the ash for the samples dried by warm air in comparison to the exhaust gases (drum dryer). The BET analysis reviled that after drying the surface area of the sawdust decreased by approximately 10%. Also, series of microscopic observations were carried out on the basis of which the manner of water accumulation in sawdust and the effect of water evaporation on the sawdust morphology were discussed. Analyzing the kinematics of the sawdust sample movement in the fountain bed, it can be concluded that the bed movement during the fountain process is affected by the size and morphology of the particles.

Based on the literature, research work and the authors’ own experience, a modification of a typical fountain dryer was proposed. Thanks to the modification the fountain dryer will be able to drying the sawdust with exhausted gases not contaminating them with additional sorting of coarse fractions that often interrupting the fountain process.

6. NOMENCLATURE

- \( A \) - is the content of volatiles in the analytical sample \([\%_{\text{max}}]\).
- \( m_1 \) - is the mass of the crucible.
- \( m_2 \) - is the mass of the crucible with the raw material being burnt.
- \( m_3 \) - is the mass of crucible with ashes.
- \( N \) - the Avogadro’s number.
- \( w_6 \) - the surface occupied by a particle in the surface of the test sample.
- \( a_p \) - the amount of the gas absorbed.
- \( S_p \) - Specific surface area
- \( S \) - air flow \([\text{dm}^3/\text{h}]\)
- \( t \) - time \([\text{s}]\)
- \( Y \) - humidity \([\%] \)
- \( T \) - temperature \([\circ C] \)
- \( V \) - Sample volume \([\text{ml}]\)

7. REFERENCES


