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ANALYSIS OF ENERGY LOSS TROUGH THE THERMAL INSULATION OF A DIGESTER

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Abstract. This analysis uses thermodynamics and heat transfer as fundamental bases for the determination of heat loss through thermal insulation in glass wool, which is installed in a eucalyptus cooking digester for cellulose extraction. This cooking requires a large consumption of steam, which today is generated through the burning of coal and black liquor, and its conscious use is important to achieve the company's sustainability goals. Through the analysis of data from the supervisory control of the process and field visits using a thermographic camera, a great loss of heat through the walls of the digester was observed. Applying the knowledge of mass and energy balance of the control volume, it was possible to determine the amount of energy lost to the surroundings and convert it into steam flow to verify its cost for the process. By doing a heat transfer analysis using the concept of thermal resistances, it is possible to assess the state of the current insulation and estimate the possible gains with a new insulation. The results obtained showed that the installation of rock wool with a thickness of 50 mm results in savings of 99% of the current steam cost and the cost of this installation has a payback time of less than 6 months of plant operation. These results reinforce the importance of carrying out periodic checks of the real state of insulating surfaces and carrying out renovations when necessary.

Keywords: Thermal Insulation, Sustainability, Thermodynamic Efficiency, Energy balance.

1. INTRODUCTION

Most steam demands in industry are for heating processes. For example, heating water, generating pure steam, heating cooking ovens, pressurizing and heating autoclaves, cooking and boiling. This is because steam is one of the most efficient and safe ways to transport thermal energy.

The process of cooking eucalyptus to extract cellulose fibers is no different, it uses a large demand for steam by direct and indirect injection in the process. In industrial pulp production plants, this cooking step is carried out in equipment known as a digester, which is one of the largest consumers of medium pressure steam in the plant.

To ensure this transport of steam and maintain its energy properties, in addition to the operational safety of the plant, a thermal insulation coating must be applied to pipes and equipment, which will also help in the efficient consumption of this fluid.

Thermal insulation is a barrier made by specific materials and products that serve to prevent the transfer of heat from one place to another or from some equipment to the environment, as is the case with industry.

Another issue that makes the efficient consumption of steam important in the industry is the demand and competitiveness of the market, in this case that of Cellulose, where the demand for more efficient and more ecological suppliers is increasing. Thus, there is an internal demand in industries to increasingly reduce their environmental impacts and production costs, to remain competitive.

But often, instead of focusing on improvements in management or production processes with adjustments to the existing model, innovation can emerge as a solution just by reformulating the way to deal with problems, making it easier to reduce costs by recovering equipment instead of investing in new technologies and obtain better results.

In line with these ideals, this work aims to evaluate the energy loss through a degraded thermal insulation of a continuous Digester used in a Kraft pulping process, at CMPC's Pulp manufacturing plant in Guaíba 1.

2. METHODOLOGY

This work is a study of a working heat engine known as a digester, it follows the fundamentals of thermodynamics and the two ways of study presented by (Çengel, 2014). The first way is the experimental study, which is when you work

testing and taking measurements in a real physical process, the second way, the analytical, is when you do calculations and mathematical analyses, assuming conditions, approximations and idealizations trying to get as close as possible. of a real process.

2.1 Control volume mass balance

To develop the mass balance, the 1st Law of Thermodynamics states that the net change in the total energy of a system during a process must be equal to the difference between the total energy received and the total energy rejected by the system during the process. The 2nd Law governs that no thermal system is perfect, as it generates energy losses in the form of heat to the surroundings. (ÇENGEL, 2013), in this way shows Eq. (1). Where Qe is the amount of heat supplied to the system, We the work supplied to the system $\Sigma Emassae$ is the sum of the energies contained in the currents entering the control volume, Ws work done by the system, Qs amount of heat lost by the system to the surroundings and $\Sigma Emassas$ is the sum of the energy contained in the currents leaving the control volume.

$$Qe - We + \Sigma Emassa_e = Ws - Qs + \Sigma Emassa_s \tag{1}$$

For the analysis of the control volume, it is necessary to know the energy balance for a steady-state flow system, which is the most suitable method due to the complexity of the equipment and thermodynamic processes, as well as under stationary conditions, that is, with time invariance. The amount of energy entering the control volume in the form of heat, work, and mass transfer must be equal to all forms of energy leaving the system. (ÇENGEL, 2013).

The net rate of heat transferred Q in (W watts) in this case can be calculated from Eq. (2), where m mass flow, enthalpy change Δh, specific heat cp and temperature delta in ΔT.

$$Q = m \ \Delta h = m \ cp \ \Delta T \tag{2}$$

To calculate this rate of heat, it is necessary to know the rate of mass entering and leaving the control volume. The mass rate m can be calculated knowing the volumetric flow rate v and the specific gravity of the fluid ρ, using Eq. (3).

$$m = \rho \ v \tag{3}$$

As the study covers the experimental part, all data for the calculations were collected from the process through supervisory control, where measurements (temperature, volumetric flow, pressure and consistency) are carried out by existing instruments that operate 24 hours a day, and for that, an average value was considered only when the process was in stability and in the nominal production of 1350 TSA/d during the year 2019. For additional data, laboratory analysis results will also be observed, which are carried out daily and weekly that help to admit some properties of fluids used in the system.

Other important data obtained through equipment data sheets are the power of the pumps used in the movement of fluids into the digester and its circulations.

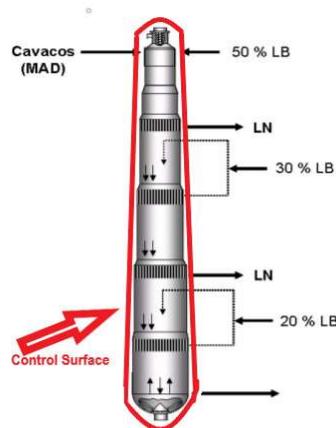To understand the control volume, Fig. 1 shows the model designed for the equipment.

Figure 1. Control volume digester to be addressed.

Analyzing the data and the process under study, it was possible to elaborate a scheme showing the control volume with all its input and output currents, as can be seen in Fig.2.
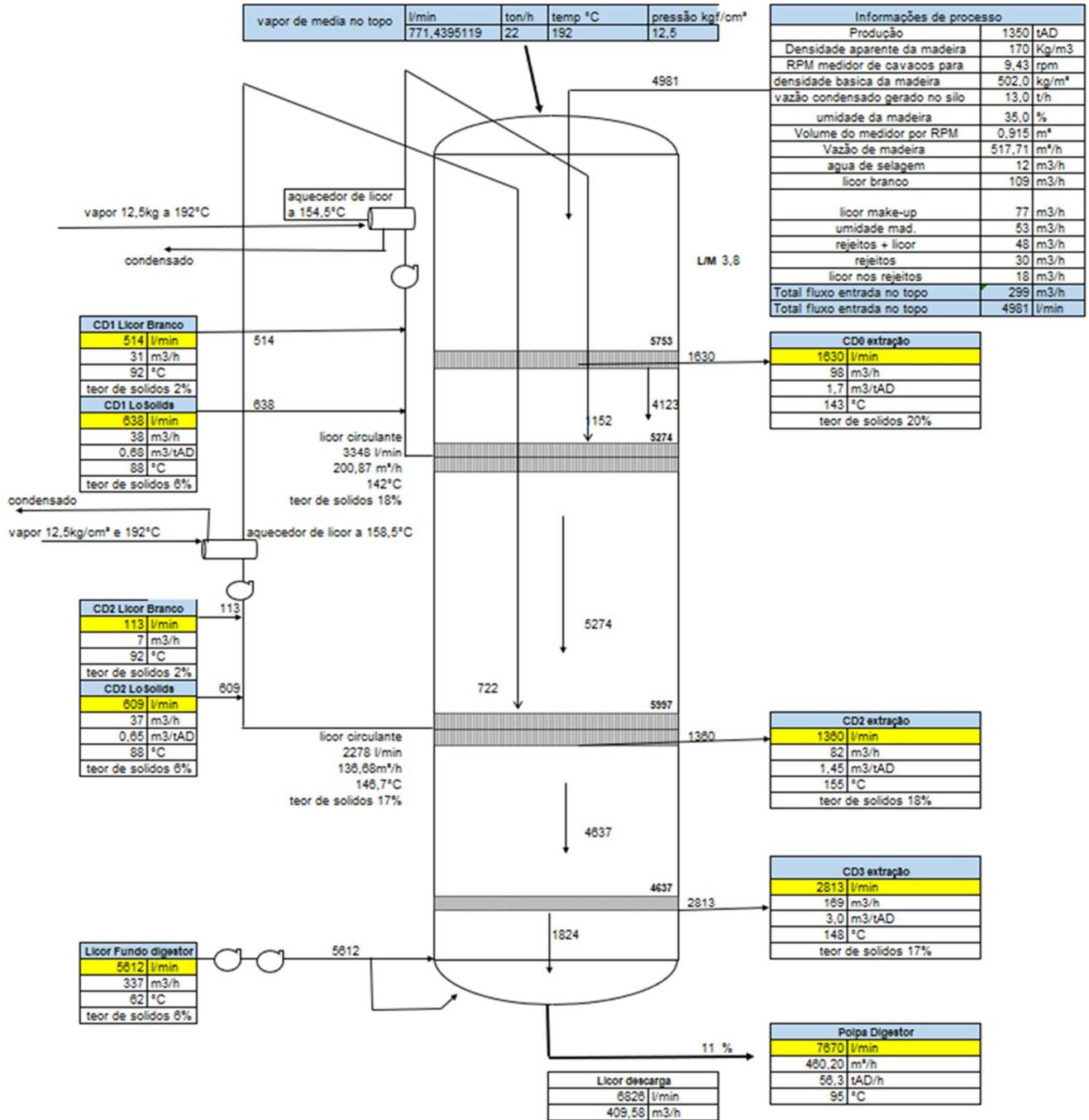
Figure 2. Control volume mass input and output data plan.

For the sequence of energy balance calculation, the scheme shown in Fig. 2.

It starts by calculating the mass flows from the volumetric flows, using Eq. 4.

It is important to point out some particularities in obtaining the mass flows of eucalyptus wood and reject. As some bibliographies indicate in case the reject considers impregnated and dry wood with a specific weight of 1530 kg/m³ and for eucalyptus wood in the form of chips fed to the process, a specific weight of 170 kg/m³ according to the analysis of the process. (SIXTA, 2006) and (FOLKEL, 2015).

As for the flow of water contained in the wood, the moisture considered via analysis is 35% and it must be considered that when vaporized in the chip silo, air is expelled from its empty spaces, which is 20% of its volume, thus having together wood an amount of 55% water/steam condensate. (FOELKEL, 2015).

For the flow of cellulose pulp from the discharge that contains 11% of fibers and 89% of washing liquor, two streams must be considered: one of washing liquor liquid with a specific weight of 946 kg/m³, and for the fibers of cellulose the specific weight considered as 1530 kg/m³. (SIXTA, 2006) and (FOLKEL, 2015).

After calculating the mass flows, the energy balance used in the CD1 and CD2 circulations of the digester must be carried out to identify the amount of heat added in the liquor streams, this calculation will be done in two ways. In the first way, the calculation will be carried out by the heat rate in each stream that passes through the heat exchanger and considering the sum of these energies as the amount of heat of each circulation, using Eq. (3) and the calculated mass flows. In the second way, the calculation of the heat rate will be carried out by the balance of steam added to the two heat exchangers used, one in each circulation CD1 which is the main cooking zone and CD2 which is the secondary cooking zone. How do you have the flow of condensate leaving the heat exchangers and the enthalpy of the liquid vapor and using Eq. (3).

Following the energy balance after obtaining the mass flows of all streams entering and leaving the control volume, the amount of energy contained in each stream will be calculated, and for the steam that is added to the digester also using Eq. (3)

It is important to note that as we only have the temperature that the fluids are at before entering the digester, zero degree (0°) was therefore admitted as the reference temperature for all fluids.

With the amounts of energy from the masses, the amount of energy added in the CD1 and CD2 circulations to the power of the pumps used in the fluids, you can perform the mass balance of the digester by applying Eq. (2), so from this balance the amount of heat being lost to the surroundings will be known, it is important to note that the control volume does not perform work.

Knowing the amount of energy lost to the surroundings in the form of heat, one can calculate the amount of steam in mass that this energy represents following Eq. (3).

2.2 Heat transfer

In this step, the methodology used to calculate the loss to the neighborhood of thermal energy that exceeds the degraded thermal insulation that is installed in the digester will be presented. It will be compared with the results of the loss calculated by the energy balance, and an analysis will be made to identify how much the permissible loss will be if the thermal insulation that has been installed today was new, and finally comparing the cost of placing a new insulation with another material with the time it would take for the steam economy to pay for this insulation.

To define the variables involved in the calculations, it starts with obtaining the temperatures of the external surface of the thermal insulation and at some points on the surface of the digester wall below the thermal insulation, these temperatures will be obtained through measurements in which a thermographic camera will be used brand Fluke model Ti400. To use the camera, it was necessary to adjust the surface emissivity. As the surfaces were opaque and oxidized, the camera was placed in automatic mode and the emissivity was $\varepsilon=0.75$.

With the thermographic camera set, images of the digester surface were obtained, which were separated into ten zones from the top to the bottom to facilitate thermal calculations, as can be seen in Fig (3). To consider the temperature of the surfaces in the calculations, an average of the temperatures of ten photos taken in each region was used.

Figure 3. Thermal photos of current digester insulation

Based on the thermal images shown and the indications of internal temperatures measured by instruments, a scheme was created with the zones that will be calculated for thermal loss to the atmosphere as shown in Fig. (4).
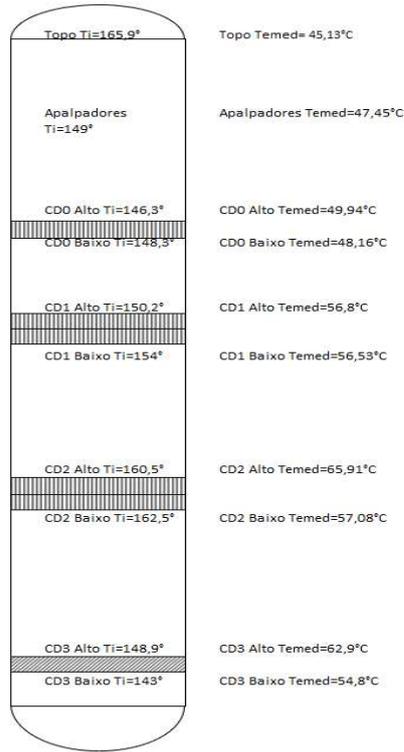
Figure 4. Indications of internal and external temperatures on the insulation surface in the 10 analyzed zones.

For the neighborhood temperature, it was established at 19,6 °C, being an annual average for the region where the digester is installed, according to statistical data from the CLIMATE-DATA website.

To define the geometric variables, such as diameter, length, and thickness, also construction materials such as wall material and thermal insulation, which will be used in the calculations, was obtained from a data sheet of the equipment. The thickness of the insulation that is installed in the digester was measured on site with the aid of a measuring tape and has a dimension of 2".

To develop these heat transfer calculations, the thermal resistance method will be used. And for the control volume in question, a scheme was developed that represented in Fig. (5).

Where it shows a sequence of resistances in series, being an internal convection resistance, a conduction in the stainless steel wall with ¼" thickness, a resistance by conduction in the wall of carbon steel with 1" of thickness, after the metallic walls there is a resistance by conduction by the original thermal insulation that is glass wool with 2" of thickness, and from the surface of the control volume where there are two resistances in parallel one of natural external convection and one resistance by radiation.
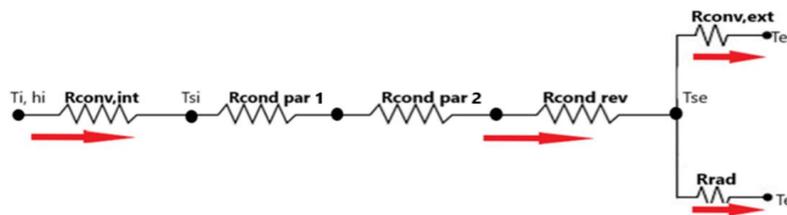

Figure 5. Resistance system to be calculated

This important concept that will be used is that of thermal resistance, knowing that resistance is the ratio between a driving potential and the corresponding transfer rate. In this way the heat transfer rate q follows Eq. (4), where one has a $\varDelta T$ and total thermal resistance Rt can take any of the three forms of heat transfer radiation, convection, and conduction. (INCROPERA, 2014). The thermal resistances follow the same way of association as the electrical resistances, being able to be in series or in parallel depending on the way in which the heat transfers are taking place.

$$q = \frac{\varDelta T}{Rt} \qquad\qquad (4)$$

For the study in question, thermal resistances are applied to a cylinder and the three heat transfer methods can be presented according to Eq. (5, 6 and 7) (INCOPERA, 2014), where *re* is the outer radius of the tube and *ri* the inner radius and *L* is the length of the transfer zone under analysis.

$$Rcond = \frac{\ln\left(\frac{re}{ri}\right)}{2\,\pi\,k\,L} \quad \text{for conduction} \tag{5}$$

$$Rconv = \frac{1}{hi\,2\,\pi\,r\,L} \quad \text{for convection} \tag{6}$$

$$Rrad = \frac{1}{hr\,2\,\pi\,re\,L} \quad \text{for radiation} \tag{7}$$

But to carry out the heat transfer calculations through the thermal resistances it is necessary to define the heat exchange coefficients for the internal convection *hi*, the external convection *he* and for the radiation *hr*. For the *he* of natural external convection, the value of 25 W/m²°C was used for gases as the fluid used is ambient air, shown in Tab. 1.

Table 1 - Typical values for convection heat exchange coefficients.

Processo	h (W/m². °C)
Convecção natural	
Gases	2 - 25
Líquidos	50 - 1000
Convecção forçada	
Gases	25 - 250
Líquidos	50 - 20000
Convecção com mudança de fase	
Ebulição ou condensação	2500 - 100000

The coefficient *hi* is not a property of the fluid and its determination is made experimentally or mathematically and depends on the boundary layer conditions, characteristics of the fluid flow nature, flow surface geometry, fluid properties and the fluid mass velocity. For this, the internal convection hi was defined as an approximation via calculation based on the amount of heat lost calculated by the energy balance where it will be used to define the heat flux transferred by the digester area. The concept of heat flux *q"* which indicates the rate of heat transfer $\dot{Q}$ per unit area *A*, can be calculated by Eq. (8) and uses the unit of W/m² (INCROPERA, 2014).

$$q" = \frac{\dot{Q}}{A} \tag{8}$$

After obtaining the heat flux *q"* the average *hi* of the defined zones in the digester will be calculated using the internal temperatures *Ti* and the surface temperatures below the thermal insulation *Ts*, applying Newton's cooling law in Eq. (9).

$$q" = hi(Ts - Ti) \tag{9}$$

In some applications, as in this case, the radiative heat exchange can be expressed in a net exchange form, using a radiative heat transfer coefficient known as *hr*, which can be defined as Eq. (10) (INCROPERA, 2014).

$$hr = \varepsilon\,\sigma\,(TSe + Tviz)\,(TSe^2 + Tviz^2) \tag{10}$$

For the radiation heat transfer coefficient *hr*, average for the zones defined for the equipment, the radiation surface temperatures will be used, which is from the thermal insulation *TSe* and the neighborhood temperature *Tviz* defined above, it will also be necessary to use the defined emissivity for thermal insulation *ε=0.75* and the Stefan Boltzmann constant *σ* using these variables in Eq. (10).

With the temperatures and coefficients established, the thermal conductivity values of the materials involved, such as the material for the digester wall, the insulation material used, which is glass wool, and the rock wool, which is the material suggested for replacing the glass wool, as it is a material with greater resistance to weather conditions and chemical product leaks imposed by the process. Conductivity show in Tab. 2.

Table 2 – Conductivity of materials.

Materials	Conductivity (W/m°C)
Carbon steel	60,5
Stainless steel	15,1
Glass wool	0,046
Rock wool	0,033

The last parameter to be defined to calculate the heat transfer from the digester to the neighborhood is the corresponding thickness of the degraded insulation *e*, using the heat flux *q''*, the conductivity of the material *k* to Eq. (11).

$$e = \frac{k\,(T1 - T2)}{q''} \tag{11}$$

Through this presented methodology, it is possible to quantify the thermal energy wasted through thermal insulation outside the process, and measure this energy in steam production cost for its generation, this cost that today for CMPC-Celulose Riograndense is U$9,35/ton of high pressure steam, considering its input, which is coal. Another source of fuel used in the generation of energy at the factory is black liquor, which is a residue from the pulp manufacturing process and as such has not cost, and its use as fuel and the consequent reuse of chemicals is what makes the process viable. of Kraft pulping.

2.3 Thermal insulation

Thermal science researchers are developing various thermal insulation systems taking advantage of different types of insulating materials, both organic and inorganic, as well as new methods to analyze the properties of insulation materials and systems. This all seeks to minimize operating costs, as well as heat loss through pipes and equipment (BAHADORI, 2014).

The material of choice Mineral rock wool available in a variety of forms. In addition to good thermal insulation properties, it can also provide sound insulation and fire retardant, great for heating and cooling systems. The application temperature range is –10 to 500°C.

With the aid of mathematical methods, the heat flux through the insulation and the applied or ideal thickness can be calculated. To calculate the applied thickness knowing the ideal heat flux *q''* for the known application, the thermal conductivity of the material *k* and the internal temperatures *T1* and surface temperature *T2*, the equivalent thickness "*e*" can be calculated using Eq. (12). (BAHADORI, 2014).

$$e = \frac{k\,(T1 - T2)}{q''} \tag{12}$$

For the heat flux transferred *q''* by the insulation, knowing the internal temperatures *T1* and the external surface *T2*, thermal conductivity *k* and the external radius *re* and internal *ri* using Eq. (13).

$$q'' = \frac{T1 - T2}{\left(\frac{re}{k}\ln\left(\frac{re}{ri}\right)\right)} \tag{13}$$

Another analysis that will be made is on the thermal efficiency of the analyzed insulations. Thermal efficiency applied to insulation does not represent an idea that energy can be partially converted into work, partially rejected, or wasted. However, it should express the effectiveness of some piece of insulation in preventing heat loss from a surface under given design conditions. It is expressed in percentage and can be described according to Eq (14), where *Ef* is the thermal efficiency and *Q* indicates the heat transfer rate (BAHADORI, 2014).

$$Ef = \frac{Q\ no\ insulation - Q\ with\ imsulatio}{Q\ no\ insulation} * 100 \tag{14}$$

Following the analytical part, based on the material presented in this work, an application of a new thermal insulation in rock wool will also be verified, evaluating the thickness necessary to reduce as much possible this thermal energy lost to the surroundings, verifying how efficient it is in relation to the cost of the heat source added to the cost of its installation material, thus being able to define the economic thickness of the insulation. This thickness can be analyzed by calculating the heat flux transferred *q''* through the insulation, at various known thicknesses. Evaluating the cost of installing the insulation together with the cost of the amount of energy lost through the insulation to the surroundings and comparing them, from the losses and the calculated costs for all thicknesses in the same working time range, thus finding the best suited for the situation.

3. DISCUSSION OF RESULTS

Analyzing Figure 6, it is remarkable the existing heat loss, comparing this loss in steam flow, the insulation if it were intact should be losing to the surroundings only 0,17 t/h of steam this would be acceptable for the installed insulation, but as the insulation is degraded by time, there is a loss of 4 t/h, result obtained by the mass balance method, compared to the steam flow used today for cooking, which is 22 t/h, this loss represents 18% of the total flow of steam that is added to the digester for heating to reaction temperature. It is a considerably high loss analyzing this energy loss in the form of steam

in 24 hours of production would represent the consumption of 95 tons more of steam, for the same production, when that admitted by the insulation should be a loss of 0,8%.
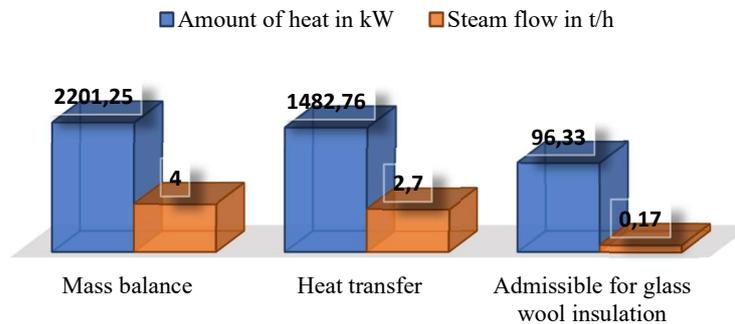

Figure 6. Amount of heat lost to proximity

Now, checking in Figure 7 the calculated thicknesses for the insulation still existing in the digester, the very low values of thickness draw attention, which justifies the heat loss calculated previously. Comparing with the thickness that the insulation should have, the calculated thickness does not reach 4%. This shows that it needs a replacement in insulation.
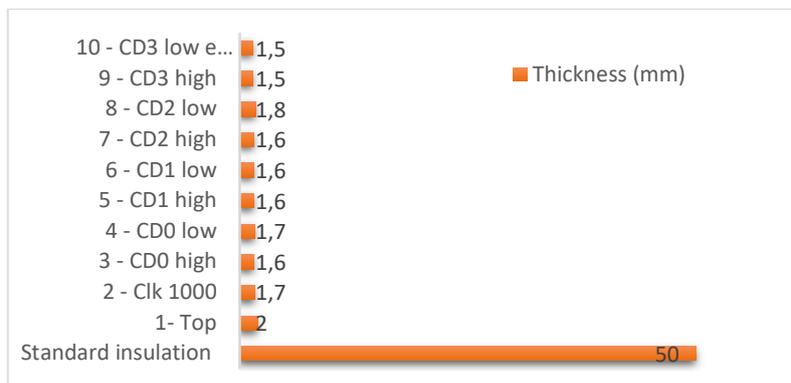

Figure 7. Thickness calculated for the existing insulation.

Figure 8 allows us to evaluate the issue of costs and define the thickness economically indicated for application in the equipment. Interestingly, in each time range, one condition is more favorable than the other, analyzing the installation in a year, the most economically favorable condition would be rock wool with 1" because the amount spent is smaller and it would be viable because it would cost less than half the cost of the actual loss in steam/year. Now taking a long-term view, 10 years would be the best cost-benefit of 3" thick insulation, the outlay would be less than the current steam loss/year and if you compare the same loss in 10 years this insulation wouldn't cost a fifth loss in steam, which tends to increase over the years if the insulation continues to deteriorate.

Finally, analyzing the entire context in which you have a pulp production plant that is over 40 years old, which requires several investments, which still does not have a defined long-term operation plan, the most effective condition in the medium term would be the 2" thick insulation, which up to 5 years is economically viable and would not be such a large initial outlay, comparing material and vapor loss would still cost half the annual vapor loss of current insulation. Installing this insulation, the savings generated in steam would pay the cost of this installation in 6 months.

Based on these data, it can be stated that any of the insulation thicknesses that were applied to the digester would generate great savings, compared to the steam costs calculated for the current condition and without any thermal insulation.
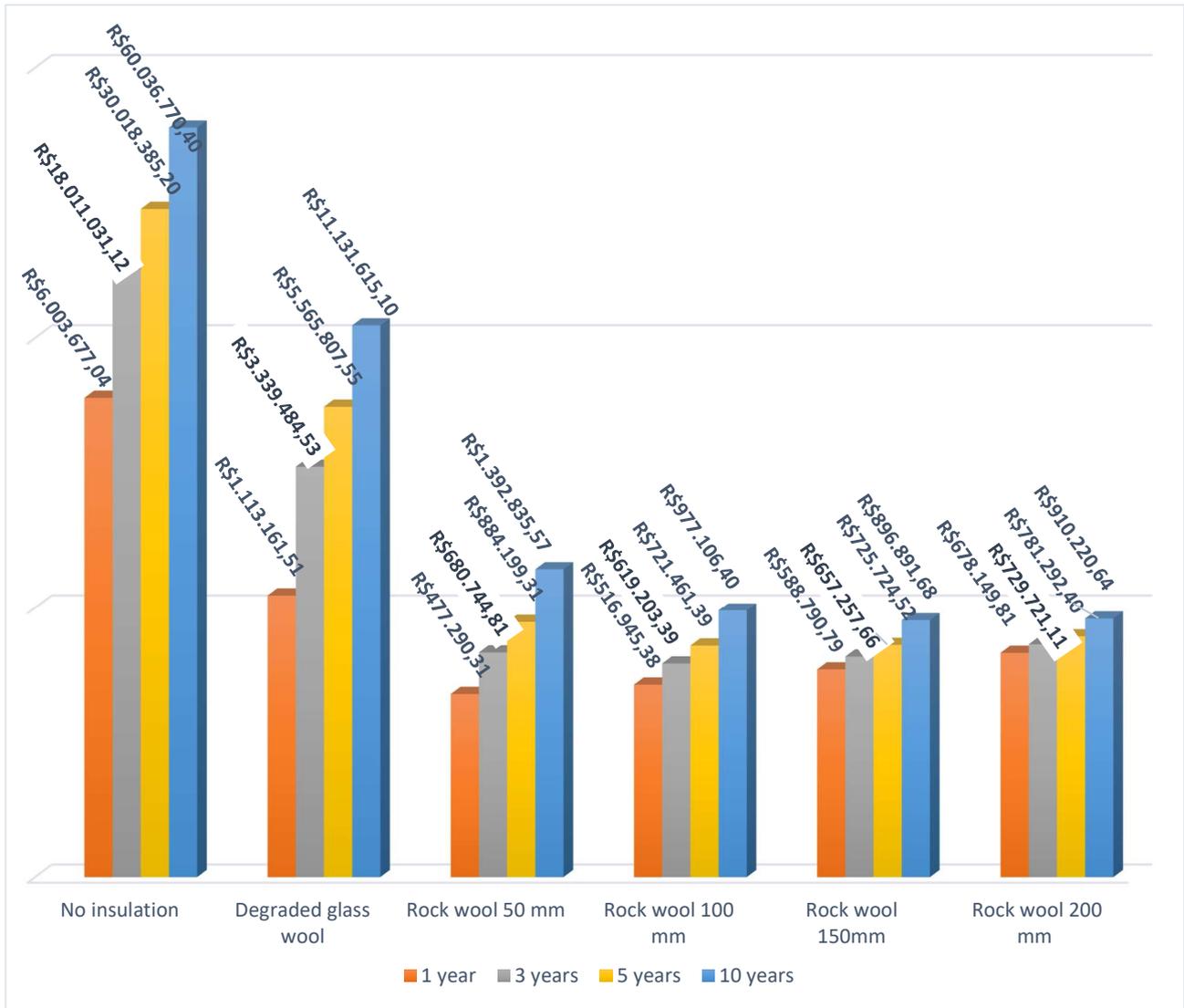
Figure 8. Comparison of total costs by insulation thickness

An interesting analysis can be seen in Figure 9 and that even degraded insulation still provides an efficiency of 80%, and when it reaches 2" thicknesses in rock wool, the gains in thermal efficiency are small. But compared to the amount of heat they are very high where the amounts of heat reached by the losses do not reach 10% of the current loss even with 1" thickness of rock wool.
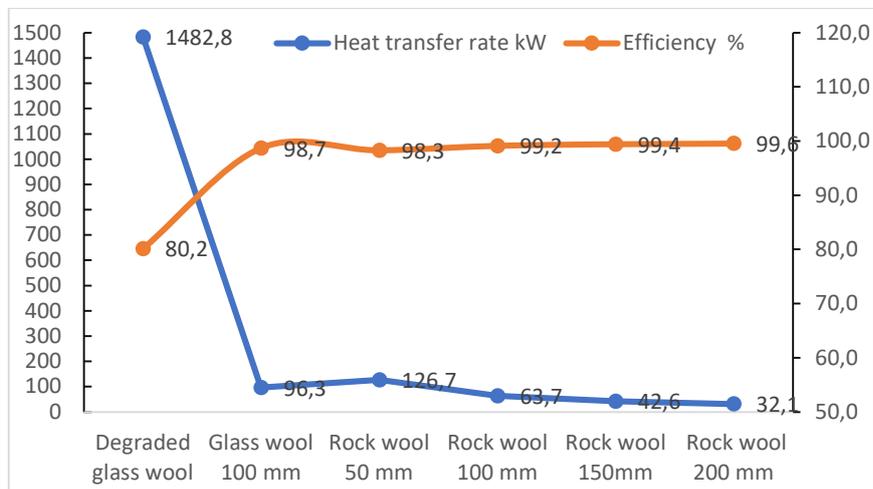

Figure 9. Comparison of efficiency and heat transfer rate by insulation.

4. CONCLUSIONS

Through this work it is possible to conclude that the methods used meet the proposed situation where it was possible to solidly analyze the heat loss from the control volume to its neighborhood as modeled, the two methods used, energy balance and heat transfer showed satisfactory results.

From these calculated losses, it was possible to determine the excessive consumption of steam necessary for the cooking of the wood and to estimate its cost for the process. And when this value was known, the size of the cost was surprising, and until then it had not received due attention.

Another important point to note is the level of degradation of the insulation, which was originally supposed to be 2" thick, and when it was estimated, it did not reach 4% of the original thickness. This confirms the high temperatures shown in the thermal images taken from the digester.

A curious fact that was verified is the level of thermal efficiency of the insulation, since the current material still had 80% efficiency with all the measured loss, and the new insulations verified have already shown an efficiency of 99%, which can be taken as a reference. is that good thermal insulation used in industry in conditions that require heating have high efficiencies, reaching very close to 100%.

Now in the economic evaluation of given rock wool insulation thicknesses, it is possible to have more than one thickness option that meets the condition. What should be taken into consideration is the time savings versus the initial cost. Even though in this evaluation the cost of installation was not obtained and that must be high due to the degree of difficulty of installation, this cost is the same for any thickness, but it would help to determine the best application period according to the chosen thickness.

An important point that must always be observed during an evaluation is the history of the plant being verified, forecast of future operation time, condition of the insulation exposure medium, equipment maintenance, insulation maintenance, to scale the insulation most suited to the application.

Finally, the result of this analysis is satisfactory, as it met all the objectives initially proposed. And after this mathematical survey of the costs with the thermal source and the insulator, it can be concluded that the application can be funded with the savings generated by the insulation, and these data can be presented to the company where the equipment is operating, aiming at efficiency, sustainability and innovation planning the next years of operation. However, the effectiveness of engineering studies for solving problems in industrial areas is evident, being able to develop more sustainable and economically viable solutions.

5. ACKNOWLEDGEMENTS

This optional section must be placed before the list of references.

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