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EXPERIMENTAL ANALYSIS OF INDUSTRIAL SOLID WASTE SOLAR DRYING

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Abstract. *The solid residue coming from the treatment of effluents generated in pickling steel wire has an inorganic nature. This residue, after the process of moisture removal by filter press, continues with high moisture content (70%). Total removal of moisture from the waste can provide a reduction of its mass to approximately 30% of the initial mass. Therefore, transport costs and landfill could theoretically be reduced by 70% of the costs without drying. Among the methods of moisture removal, drying has shown particularly interesting. The use of solar energy to promote drying of the residue study is technically and economically feasible. Environmental benefits are presented, due to its characteristic exemption for renewable and emission of greenhouse gases. This study aimed to evaluate the drying of industrial solid waste, using an active integrate solar dryer. The thermal properties and the thermal efficiency of operation of the device to different operating conditions were studied. Experimental tests were developed to evaluate the operation of a solar dryer, in order to increase the thermal efficiency and improve the uniformity of drying. The instantaneous thermal efficiency of the dryer varied 9.4% to 28.2%. In the drying experiments, the drying efficiency ranged from 2.4% to 3.5%.*

Keywords: *Solar drying; solid waste drying; thermal efficiency analysis.*

1. INTRODUCTION

For compliance with Brazilian environmental legislation, the solid waste generated in the production of steel wires shall be deposited in landfill and licensed. This waste has moisture content of approximately 70%, salts (calcium, iron, chlorides and sulfates) and metals (zinc, copper and lead) as described by Oliveira (2010). The cost of transportation and disposal of this waste is significant for the industry, and it is proportional to its mass. The reduction of the moisture content would reduce the product mass and reduce the transport and disposal costs. Drying is an interesting method of moisture removal.

The natural sun drying natural requires small investments, but is very slow and may present moisture absorption by the product in wet periods and incomplete drying. The drying in solar or artificial dryers could significantly contribute to improve the quality and reduce the time of the drying process. Artificial dryers promote fast drying. Nevertheless, they consume a considerable amount of energy (fossil, electric or otherwise) to heat the drying air and have high costs. Solar dryers can be an interesting alternative. Due to seasonal solar availability and randomness of climatic conditions, the drying airflow is subject to vary. Nevertheless, solar dryers promote faster and more effective drying than the natural sun drying, with significantly lower costs than artificial drying, since solar energy used for heating the air flow has no direct costs. In this context, a solar dryer for drying the solid residue has been designed and studied.

Some researches about drying of waste have recently been developed, like Salihoglu et al. (2007), Ohm et al. (2009) and Fadhel et al. (2011). Moreover, solar dryers have been recently developed for other applications, such as Forson et al. (2007), Sarsavadia (2007), Sreekumar et al. (2008), Ferreira et al. (2008), Sethi Sadhna (2009), Montero et al. (2010), Singh (2011), Banout et al. (2011), Fudholi et al. (2010) and Maiti et al. (2011).

The main objective of this work is to perform an experimental analysis of the operation of a solar dryer. The drying product used was industrial waste from the production of steel wires. The influence of the solar radiation on the moisture content was presented, as well as drying curves and thermal efficiency of the process.

2. MATERIALS AND METHODS

2.1. Design and construction of the system

It was designed and built a small-scale solar dryer, in order to assess the feasibility of solar drying of waste products. The dryer (Fig. 1) consists of a cover glass and a wood structure (with low weight and high mechanical resistance), internally and externally coated with black galvanized steel sheets, with internal insulation of glass wool. The solar

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dryer is 1.8 m long, 1.0 m wide, and a height of 0.35 m in the heating chamber and of 0.5 m in the drying chamber. The drying chamber area is 0.495 m^2 (0.9 m x 0.55 m) and the solar collector area is 0.99 m^2 (0.9 m x 1.1 m). The estimated drying capacity is approximately 2 kg.

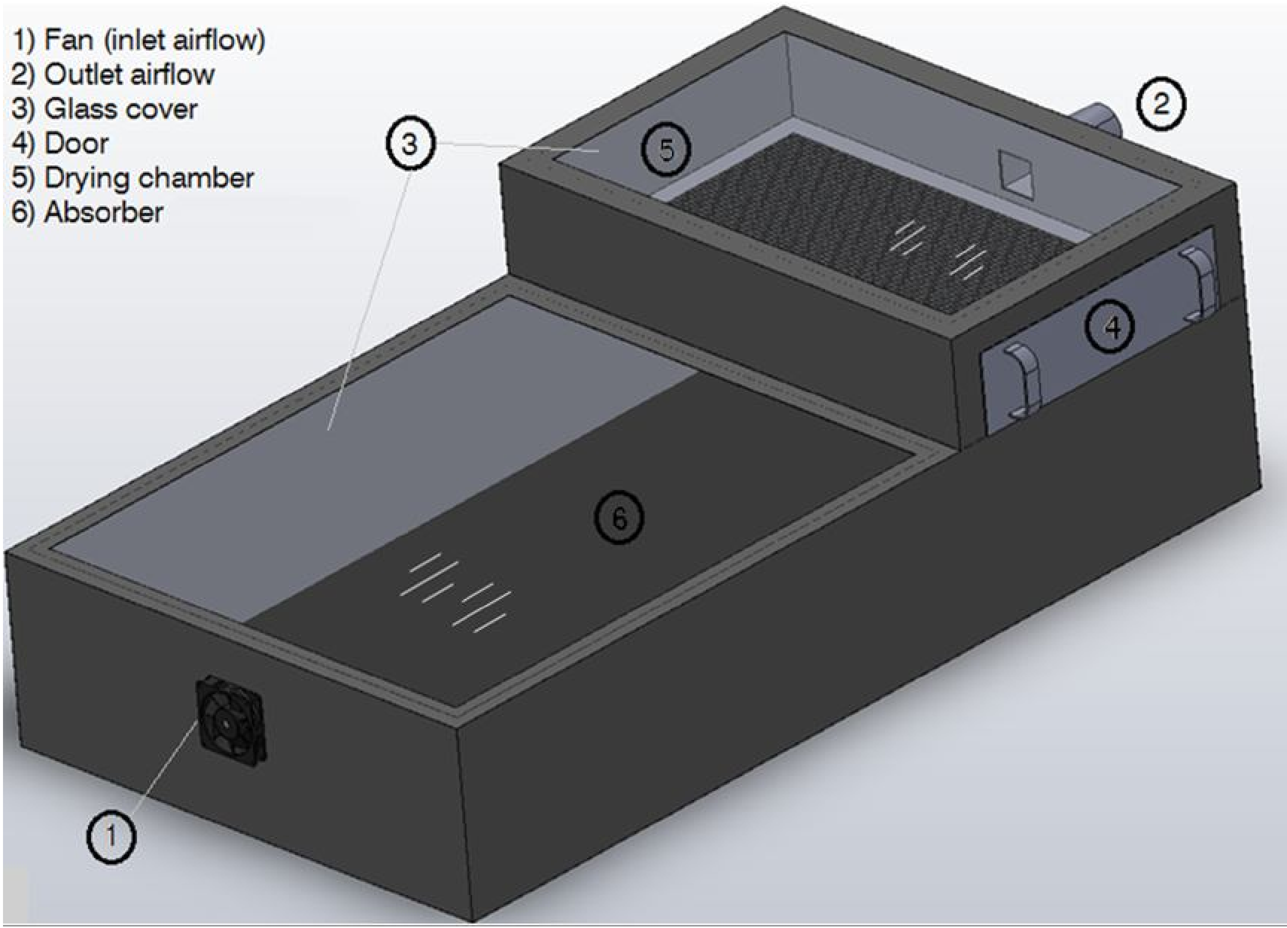

Figure 1. Schematics of the solar dryer

In the dryer, part of the incident solar radiation crosses the glass cover and reaches the absorber (painted matte black to enhance the absorption of the solar radiation). The airflow enters the dryer at ambient temperature, is heated by the absorber and crosses the drying chamber in which the drying product is placed. The hot airflow removes moisture from the product and leaves the dryer through a straight pipe section with screens. The product is inserted and removed from the drier through the side door.

2.2. Instrumentation and experiments

To collect all data needed to evaluate the dryer's performance, several systems to perform measurements and data acquisition were utilized. Thermometers (ICEL TD-880, with maximum uncertainty of ±0.6°C) were used to measure the ambient temperature. The air velocity and humidity at the outlet of the dryer was measured with a propeller thermal-anemometer (ICEL model AN-4870, with a global uncertainty of ±3% for each parameter). The product weight loss during the drying process was measured with a digital analytical balance (with uncertainty of ±0.2g). The humidity and temperature of the inlet airflow were measured with a propeller thermometer data logger (ICEL HT 4000, with a global uncertainty of ±3% for humidity and 1°C for temperature). The solar radiation was measured with a PSP (Precision Spectral Pyranometer), with a global uncertainty of ±1%, connected with a data acquisition Agilent 34980. An uncertainty analysis in accordance with a 95% confidence interval was performed to estimate the errors in the experimental data (Moffat, 1988; ISO, 1998).

The residue samples were cut into cylindrical shape with a diameter of 26.5 mm and thickness of 16.5 mm. The samples were dried in trays with 10cm x 10cm. In the tests of evaluating the initial moisture content of the samples, a drying oven was used. It has a control system of temperature and air renewal, and an internal volume of 0.04 m^3. In the initial humidity test, 10 samples were kept inside a greenhouse at a temperature of (105 ± 2)°C for 24 hours. This

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procedure was established by the procedure NBR 9939 (1987) and NM 105 (1999), suggested by Aguirre and Gasparino Filho (1999).

The tests were performed in a well-drained and flat location, free from any obstacles. The dryer was positioned with a tilt angle of 30° facing north. This tilt angle was defined as the absolute value of local latitude plus 10º, in order to maximize efficiency annual, as suggested by Duffie and Beckman (2006).

To evaluate the drying 12 trays were used, with 4 samples each (Fig. 2). The samples were weighted at intervals of 15 minutes. The solar drying tests were performed in November, with 8 hours of duration (07h00 to 15h00, solar time). The parameters evaluated were the temperature and the humidity of the air at the inlet and outlet of the dryer, the velocity of the air at the dryer outlet and the solar radiation incident on the dryer.

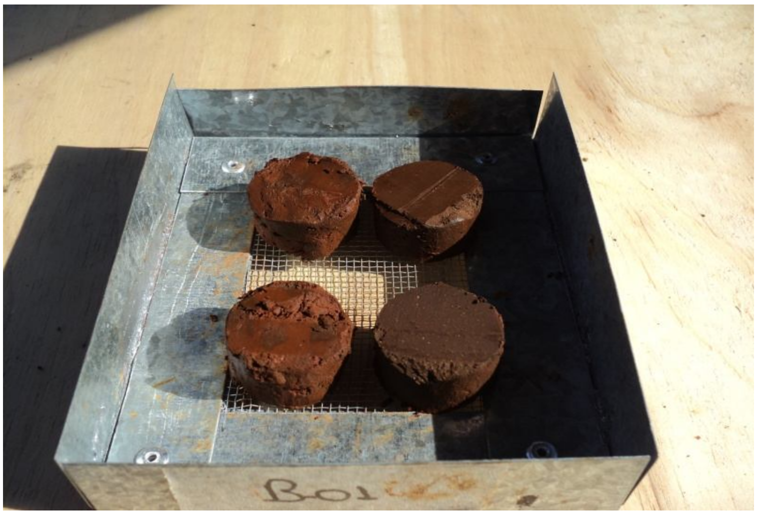

Figure 2. Residue samples

3. MATHEMATICAL MODEL

According to Leon et al (2002), the instantaneous thermal efficiency of a dryer is:

$$\eta_T = \frac{\dot{m}\left(h_{out} - h_{in}\right)}{A.G} \tag{1}$$

where $\dot{m}$ is the mass airflow, h_{in} and h_{out} are the specific enthalpies of the inlet and outlet of the dryer, A is the collector area and G is the hemispheric solar radiation.

In a drying process, Leon et al (2002) suggest that the drying efficiency is given by

$$\eta = \frac{\int \dot{m}_{H2O}.h_{lv}\, dt}{\int A.G} \tag{2}$$

where $\dot{m}_{H2O}$ is the mass airflow of the water removed from the product, and h_{lv} is latent heat of vaporization.

The initial moisture content (wet basis) $U_{i(BU)}$ is obtained based on the initial (m_i) and final (m_f) sample mass

$$U_{i_{(BU)}} = \frac{m_i - m_f}{m_i} \tag{3}$$

The instantaneous moisture content (wet basis) of the samples ($U_{x(BU)}$) was obtained based on the instantaneous (m_x) and initial (m_i) mass of the sample and on the initial moisture content:

$$U_{x_{(BU)}} = 100\% - [\frac{m_i}{m_x} \times (100\% - U_{i_{(BU)}})\ ] \tag{4}$$

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4. RESULTS

The tests shown that the initial moisture content of the residue was 68%. In order to evaluate the influence of the climatic conditions on the drying process, nine tests were performed.

Table 1 presents the average daily solar radiation (G), ambient (T_{amb}), mass airflow ($\dot{m}$), rise of temperature inside the dryer (ΔT), ambient relative humidity (ϕ_{amb}) and airflow relative humidity (ϕ_{esc}) obtained in the drying tests for each day. It can be noticed that the higher average incident solar radiation and the higher temperature rise occurred in Nov-06, and the lower average incident solar radiation and the lower temperature rise occurred in Nov-07. Nov-06 and Nov-07 also correspond to the lower and higher average relative humidities of the airflow, respectively.

Table 1. Experimental results for average daily climatic and flow properties

Data	G (W/m^2)	T_{amb} (°C)	$\dot{m}$ (kg/s)	ΔT (°C)	ϕ_{amb} (%)	ϕ_{esc} (%)
Oct-26	(542.0±7.6)	(24.9±0.6)	(0.00653±0.00027)	(21.7±0.6)	(49.6±1.5)	(15.7±0.5)
Nov-03	(503.5±7.0)	(23.2±0.6)	(0.00676±0.00028)	(21.8±0.6)	(45.2±1.4)	(14.2±0.4)
Nov-04	(604.3±8.5)	(24.4±0.6)	(0.00693±0.00029)	(26.8±0.6)	(46.9±1.4)	(15.8±0.5)
Nov-05	(623.6±8.7)	(24.7±0.6)	(0.00697±0.00029)	(27.7±0.6)	(45.7±1.4)	(14.6±0.5)
Nov-06	(685.7±9.6)	(26.0±0.6)	(0.00680±0.00029)	(29.0±0.6)	(37.3±1.1)	(12.1±0.4)
Nov-07	(376.7±5.3)	(26.1±0.6)	(0.00690±0.00029)	(16.1±0.6)	(39.4±1.2)	(19.3±0.6)
Nov-08	(526.7±7.4)	(26.8±0.6)	(0.00689±0.00029)	(22.8±0.6)	(43.6±1.3)	(15.8±0.5)
Nov-09	(542.1±7.6)	(25.7±0.6)	(0.00682±0.00029)	(22.5±0.6)	(46.1±1.4)	(17.9±0.5)
Nov-11	(623.3±8.7)	(27.2±0.6)	(0.00670±0.00028)	(22.9±0.6)	(40.2±1.2)	(18.0±0.5)

Figure 3 shows the drying curve of the solid residue, made on Nov-07, the day with lower incident solar radiation. The moisture content (wet basis) of the product is shown as a function of the solar time. Instantaneous solar radiation data is also presented. Solar radiation data indicate a significant atmospheric attenuation. With the reduction of solar radiation, the slope of the dry content decreased. It can be explained by the reduction of the internal temperature of the dryer, reducing the velocity of the drying. As a consequence, the final moisture content of the product moisture is high.

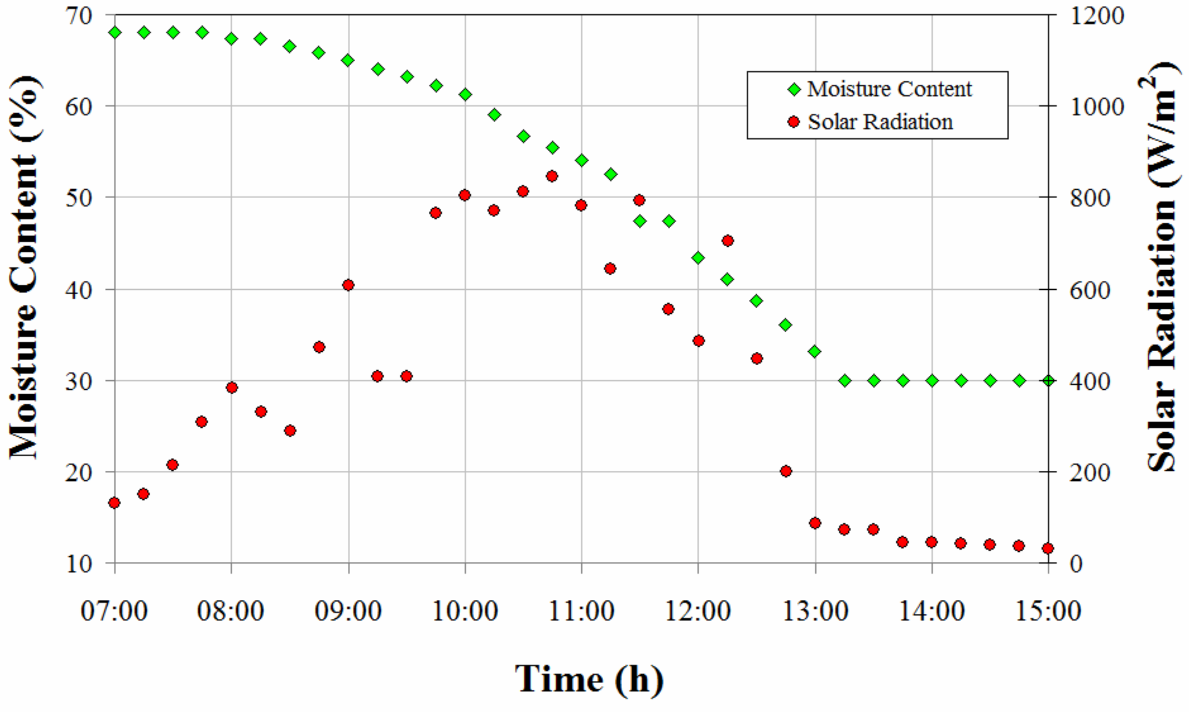

Figure 3. Drying curve in Nov-07

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Figure 4 shows the drying curve for Nov-06, the day with higher average incident solar radiation and lower atmospheric attenuation. It can be seen that the drying curve has a steeper gradient than the drying curve shown in Fig. 3, indicating a higher velocity of drying. This increased rate of drying was achieved due to the increased incidence of solar radiation and higher temperature of the airflow in the dryer. Furthermore, it can be seen at the end of the test, the final moisture content of the product achieved was higher than the obtained on Nov-07.

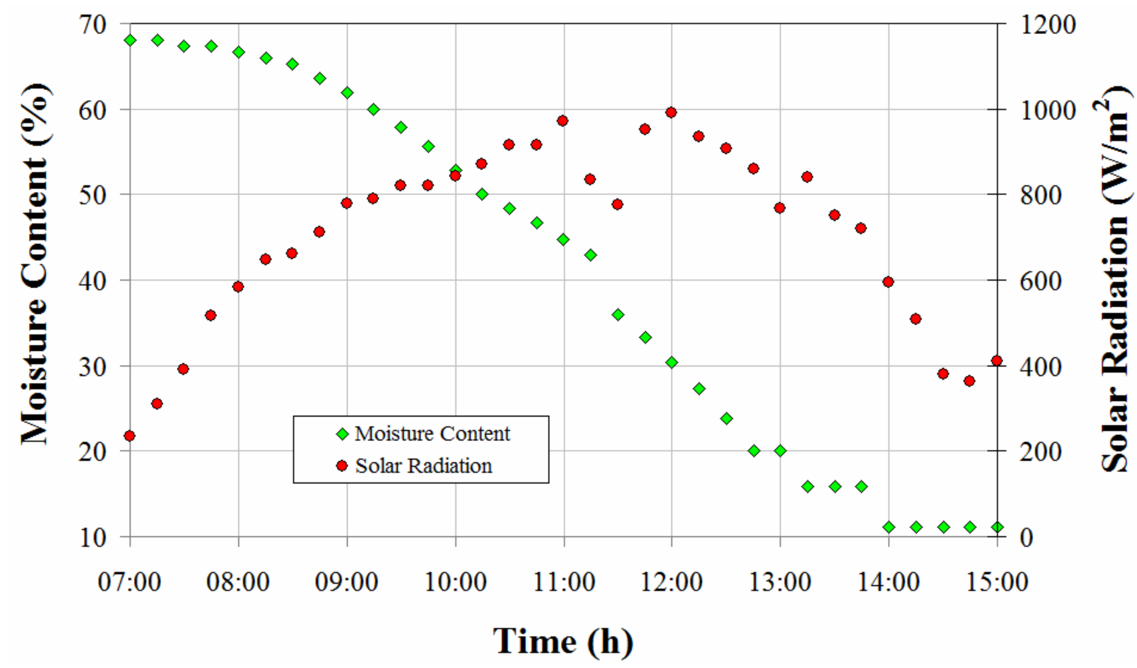

Figure 4. Drying curve in Nov-06

Figure 5 shows the average daily solar radiation and the final moisture content of the product, for each day of tests. It can be noticed that higher average solar radiation (which promotes higher internal temperatures of the airflow, as seen on Table 1), promote lower final moisture contents on the residue. Moreover, since the velocity of drying is higher, increased solar radiation promotes a more complete drying for a fixed period.

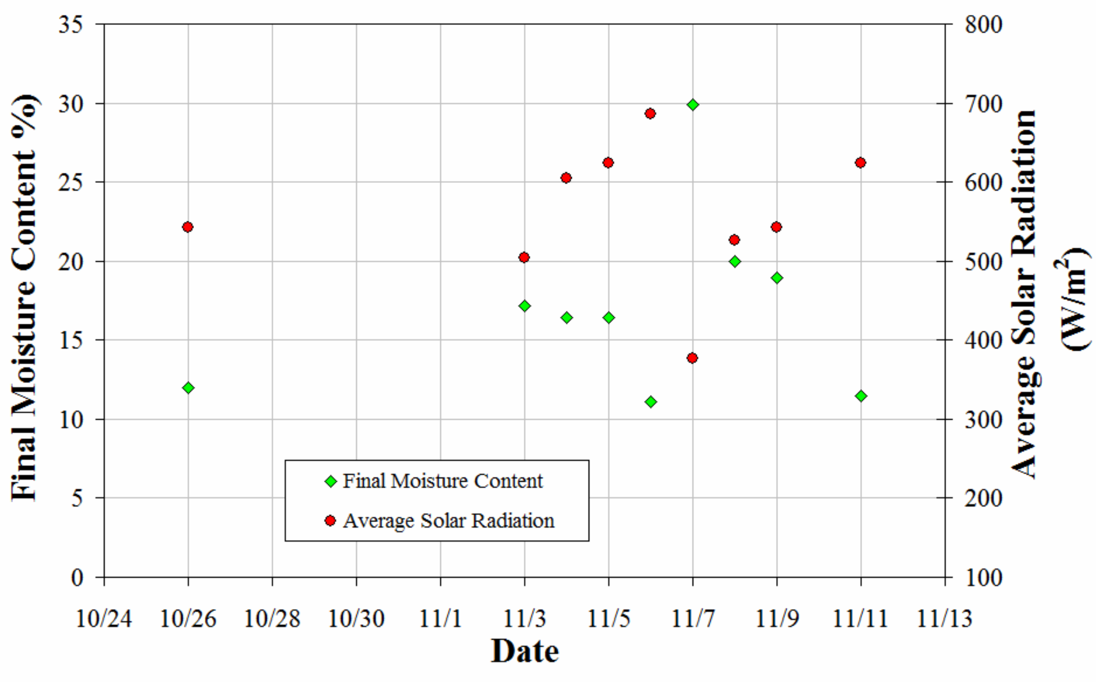

Figure 5. Final moisture content and average solar radiation

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The drying efficiency of the device can be observed as a function of the average rise temperature of the airflow inside the dryer in Fig. 6. It can be noticed that the drying efficiency of the device varied from 2.4% to 3.5% in the tests. The highest efficiency was achieved on Nov-07. It is interesting to note that the drying efficiency decreases with the increase in the average rise temperature between the inlet and outlet dryer. This behavior can be explained by the fact that the drying efficiency is defined as the ratio between the latent energy of moisture removal of samples and the available energy. For a same period of tests, the latent energy varied only slightly, and the available energy varied significantly with the incident solar radiation and airflow temperature.

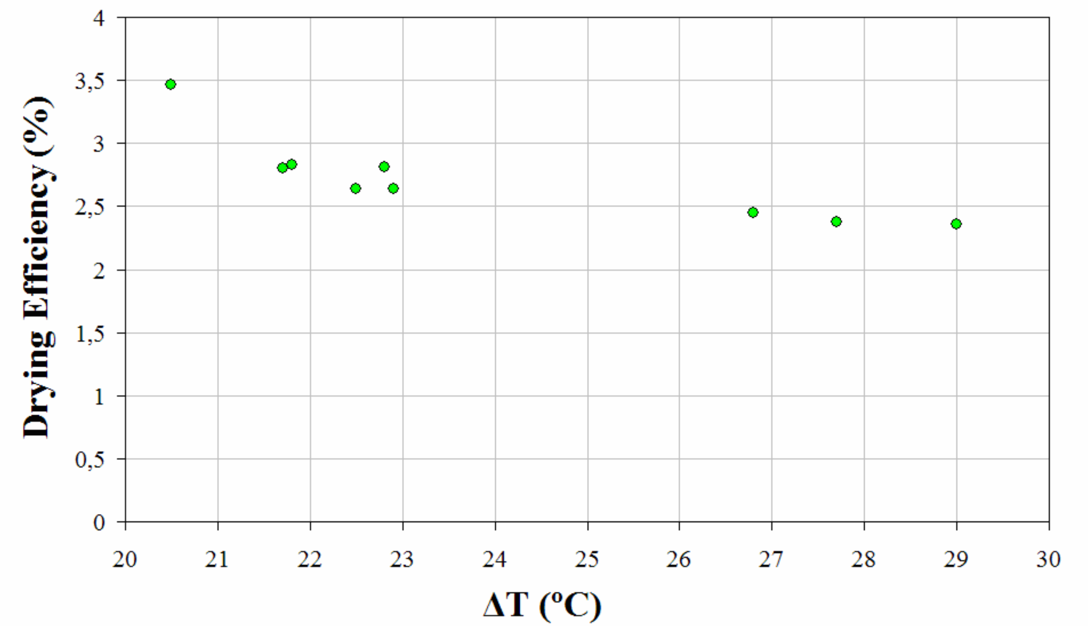

Figure 6. Drying efficiency

Figure 7 presents the instantaneous thermal efficiency of the dryer. The instantaneous thermal efficiency varied from 9.4% to 28.2% with an average value of 16.7%. Although the results present a wide spread of results, it can be a slight tendency of the dryer thermal efficiency to increase with the rise temperature in the dryer. This large dispersion can be partially explained by the thermal inertia of the device in periods of fast variation of solar radiation. The instantaneous reduction of solar radiation does not cause a fast response on the ambient and airflow temperatures. Therefore, there is an abrupt increase in the thermal efficiency, causing a great dispersion.

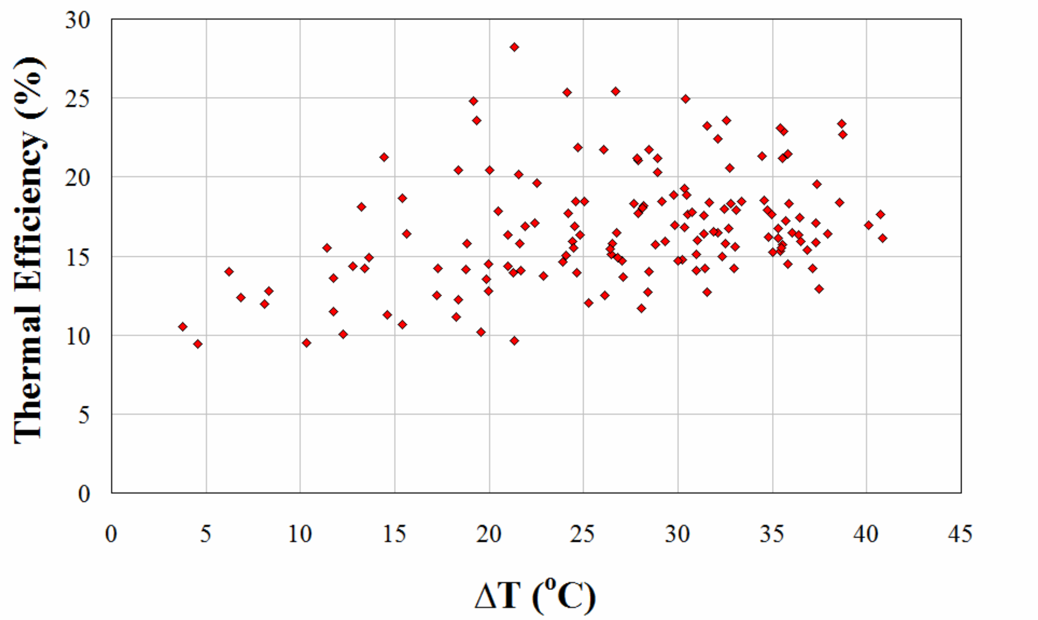

Figure 7. Thermal efficiency

5. CONCLUSIONS

In this work it was presented an analysis of the technical feasibility of a solar cabinet dryer. The drying product was industrial residue of an effluent treatment plant of steel wire. In order to perform the feasibility analysis, the airflow parameters and environmental conditions were monitored.

Experimental tests have shown that higher solar radiation levels promoted higher temperature rises and lower relative humidities in the drying airflow. Moreover, the drying curve analysis showed that higher solar radiation levels the drying accelerated the drying process and led to lower final moisture content of the drying product. During the drying tests, it was observed that the instantaneous thermal efficiency of the solar dryer varied from 9.4% to 28.2%, and the drying efficiency of the device varied from 2.4 to 3.5%.

The theoretical drying capacity of the built solar dryer is 2 kg of wet waste, during the period of sunlight. The use of similar dryers in industrial scale will depend on the amount of waste produced. For a lot of waste, many dryers will be needed, as well as a very large drying area.

It can be concludes after the tests with the solar dryer that the device is technically feasible and it is be able to effectively dry the solid waste from the production of steel wires. Furthermore, the use of an abundant and renewable energy source to generate the drying airflow ensures the economic viability of the dryer.

6. ACKNOWLEDGEMENTS

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