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EVALUATION OF ENERGY EFFICIENCY IN TRADITIONAL TOBACCO CURING OVENS [1]

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ABSTRACT

Tobacco has become one of the most important crops in Colombia, generating employment for both skilled and unskilled workers. We have found several problems in the post-harvesting of tobacco, one of which concerns the high cost of the fuel used in curing ovens. We therefore evaluated the traditional burner-type heat exchanger to determine fuel use efficiency. The information obtained clearly shows the great difficulty of maintaining stable temperatures inside the oven with this system of heat transfer by natural convection, creating environmental conditions that deviate significantly from those suggested for this process. These variations depend largely on the frequency of loading fuel into the burner. We also found that the energy efficiency when using coal is less than 10%.

KEYWORDS: Tobacco curing, heat exchanger, thermal efficiency, oven.

EVALUACIÓN DE LA EFICIENCIA ENERGÉTICA EN LOS HORNOS TRADICIONALES DE CURADO DE TABACO[3]

RESUMEN

El cultivo del tabaco se ha convertido en uno de los más importantes en Colombia, generando empleo a mano de obra calificada y no calificada. En la poscosecha del tabaco se han detectado varias problemáticas a resolver, una de ellas la concerniente al alto costo del combustible empleado en los hornos de curado. Por ello, se realizó una evaluación al intercambiador de calor tradicional tipo hornilla para determinar la eficiencia en el uso del combustible. La información obtenida deja en evidencia la gran dificultad que se tiene con este sistema de transferencia de calor por convección natural para mantener temperaturas estables al interior del horno, generando condiciones ambientales que se alejan considerablemente de las previstas para este proceso, dependiendo estas variaciones, en gran medida, de la frecuencia de cargue de la hornilla, encontrándose además, que la eficiencia en el aprovechamiento de la energía entregada por el carbón es menor del 10 %.

PALABRAS CLAVES: curado de tabaco; intercambiador de calor; eficiencia térmica; horno.

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AVALIAÇÃO DA EFICIÊNCIA ENERGÉTICA NOS FORNOS TRADICIONALES DE CURA DE TABACO

RESUMO

O cultivo de tabaco tornou-se um dos mais importantes na Colômbia, criando postos de trabalho para mão de obra qualificada e não qualificada. Em pós-colheita do tabaco se tem identificaram vários problemas a serem resolvidos, um delas ao relativo ao elevado custo do combustível utilizado nos fornos. Portanto, realizou se uma avaliação tradicional ao intercambiador de calor tradicional tipo hormilla para determinar a eficiência do tipo de combustível A informação obtida mostra claramente a grande dificuldade que temos com este sistema de transferência de calor por convecção natural para manter as temperaturas estáveis no interior do forno, a criação de condições ambientais que se desviam significativamente daquelas exigidas para este processo, dependendo destas variações em em grande medida, a frequência da carga do queimador também descobriu que a eficiência na utilização da energia fornecida pelo carvão é inferior a 10 %.

PALAVRAS-CHAVE: rapé cura; trocadores de calor; fornos; eficiência térmica.

1. INTRODUCTION

For more than a century, tobacco has been linked with the economic, cultural, and social life of Colombians. As in many parts of the world, tobacco is an important source of work and income for farmers in Colombia, while at the same time providing considerable financial resources. The tobacco industry also invigorates the economy through its connections with other sectors such as transportation, the cardboard industry (for boxes), the graphic industry, advertising, marketing, and the media (due to the large investment this sector makes to promote its products) (Ministerio de Agricultura y Desarrollo Rural, 2005).

For the case of the Department of Huila, the tobacco sector has remained stable during periods of agricultural crisis in Colombia, and in recent years, it has had an upturn with a resulting increase in areas planted. However, we have detected stages in the harvest process and during post-harvest that cause large economic losses for producers. During the harvest phase, losses are caused by pickers who do not have the appropriate training or who do not apply this knowledge to their work. During the tobacco leaf curing phase, we have found deficiencies in oven construction, fuel use, control of the curing process, and the final selection of dry material which negatively impact the quality of the product to be sold and, therefore, the value of the final transaction. In general, we understand curing to mean the changes undergone by recently harvested leaves under certain conditions of temperature, moisture, and time. It is a vital process that is therefore among the phenomena of ageing or starvation of the recently cut leaves. The purpose of curing is to produce a dry leaf with the proper physical properties and a balanced chemical composition on order to satisfy the consumer (Coltabaco S.A., 2007). During this process, the leaf loses approximately 90% to 15% of its moisture content.

The heat for curing is produced by heaters or burners and distributed throughout the interior of the oven. With the help of ventilation systems, the hot air removes the moisture from the leaf. The interior of the oven also has a structure formed by beams or bars that support the racks filled with leaves ready to begin the curing process (SENA Regional Santander, 2005). Conventional or traditional ovens are the most commonly used in Colombia, and they are generally built with dimensions of 6m x 6m x 6m or of 7m x 7m x 7m and have an average curing capacity of 700 kg of dry tobacco per session (**Figure 1**). It is considered that an oven of these dimensions is sufficient to cure and dry the tobacco produced by 2.5 hectares of plantation (SENA Regional Santander, 2005).

The relationship between the quantity of heat effectively used for evaporation and the quantity of heat used is defined as thermal efficiency. In well-designed grain drying ovens, efficiencies of approximately 60% to 65% are obtained (Castillo, 1984). Zamora et al. (2005) made a technical analysis of the operation variations of a tubular air heater (TAH) used for drying coffee. It initially used only 0.4% of the energy released by combustion, but this efficiency was raised to 10.5%, considered by the researchers to be the maximum heat transfer efficiency for a TAH.

The following has been found in the case of exchangers used with liquid fuel burners (Roa et al., 1999):

- An exchanger with a winged surface easily allows for 50% efficiency.
- It is rare to obtain efficiency levels above 40% for exchanges without wings.
- For burning coke, coffee growers generally use equipment with low efficiency (a maximum of 30%).

In an evaluation of a bulk-curing stove used for curing tobacco, Altobelli (2010) found that its energy efficiency was 29.21%, which is considered low. Using a forced-air heat exchanger that uses coal or coffee husks as fuel, Cerquera & Ruiz (2007) found the following fuel use efficiencies in the stages of curing Virginia tobacco with coffee husks: 70% in the yellowing stage, 66% in the color fixation stage, and 69% in the vein drying phase; and with coal: 67% in the yellowing stage, 63% in the color fixation stage, and 74.2% in the vein drying stage.

According to De Castro (1995), the curing process of Virginia tobacco in driers is the agricultural product drying process that uses the most energy. According to Ryan et al. (1988), cited by De Castro (1995), while drying grains generally consumes 7 liters of diesel fuel per ton of dried product, tobacco drying consumes 670 liters per ton of cured product. According to Suggs (1992), cited by De castro (1995), Virginia tobacco curing is a process with particularly intensive energy consumption due to the leaves' high moisture content (80-90% base moisture) when they are put into the dryer. Therefore, the quantity of water that must be eliminated during the process is very high: approximately 5 to 10 kg of water must be evaporated for each kilogram of cured tobacco.

This is even more relevant given that there are more than five hundred (500) traditional ovens in the Department of Huila (Caicedo, 2005) and they represent a significant economic investment. Therefore, this exploratory study determined and quantified curing process variables that allow us to establish the use efficiency for the energy released by fuel during the curing process in traditional tobacco curing ovens.

2. MATERIALS Y METHODS

- The study was completed in the municipalities of Campoalegre and Garzón in the Department of Huila. A total of three batteries of ovens were evaluated, one in Campoalegre and two in Garzón, for a total of nine ovens. For each, readings were made at intervals of two hours during the entire curing process of the variables as follows:
- Monitoring surface temperatures at six points in the heat exchanger tube and one point at the combustion gas output toward the chimney using an Extech EA 15 thermocouple with a type-K surface probe and glass thermometers (see **Figure 1**).
- Dry-bulb and wet-bulb temperature readings with a wick synchrometer.
- Relative moisture readings.
- Quantification of fuel consumption and monitoring when fuel was loaded into the oven by operators

2.1. Calculation of energy provided by natural convection to the oven's interior environment through the heat exchanger

In order to calculate the energy provided to the environment by the exchanger, we used **Equation 1**, whose film coefficient for natural convection was estimated with the help of **Equations 2**, **3**, **4**, and **5** (Holman, 1996). The values found were used to obtain the energy transmitted per unit of heat exchanger length into the oven's internal environment (**Equation 6**).

$$Qconvección = hcA(Tw - T\infty) \quad (1)$$

In which:

$Q_{convección}$: Convection energy delivered by the heat exchanger to the environment in W

h_c: Coefficient of convective heat transfer in $W \cdot m^{-2} \cdot {}^{o}C^{-1}$

A: Heat exchange tube surface area in m^2

T_w: Exchanger surface temperature in °C

T_∞: Average temperature of interior environment in °C

The average temperatures of the surface (T_w) and the environment (T_∞) correspond to the readings made at the measurement points on the heat exchanger and the interior environment of the oven in the three curing stages.

The natural convection film coefficient for each of the curing stages was calculated by applying the following procedure:

$$GrPr = \frac{g\beta(Tw\text{-}T\infty)\ d^3Pr}{v^2} \quad (2)$$

In which:

Gr: Grashof number

Pr: Prandtl number

g: Gravitational acceleration ($m.s^{-2}$)

β: Coefficient of thermal expansion of air (K^{-1})

d: Diameter of exchanger tube (m)

v: Kinematic viscosity of air ($m^{2.}s^{-1}$)

The absolute film temperature is found by applying the following equation

$$T_f = \frac{T_w + T_\infty}{2} + 273 \quad (3)$$

In which:

T_f : Film temperature (K)

T_w: Surface temperature of the heat exchanger tube (°C)

T∞ : Surrounding air temperature (°C)

The Nusselt model is calculated with the following equation:

$$Nud = c(GrPr)^m \quad (4)$$

In which:

Nud: Nusselt number

c and m: Constants to be used in **Equation 4** (Holman, 1996)

Once Nud has been calculated, the heat transfer coefficient is found with **Equation 5**:

$$hc = \frac{k \text{ x } Nud}{d} \quad (5)$$

In which:

k: Thermal conductivity. ($W\ m^{-1}.°C^{-1}$)

d: Diameter of exchanger tube (m)

The energy transmitted by unit of heat exchanger length to the oven's internal environment is obtained applying **Equation 1**:

$$\frac{Q}{L} \quad h_c\ \pi d\ (T_w - T_\infty) \quad (6)$$

L: Total length of heat exchanger tube (m)

2.2. Calculating the energy required for each phase of the curing process

In order to calculated the energy needed to heat the domain environment when moving from one phase to another in the curing process, as well as the energy required to maintain temperature and moisture conditions at an average value throughout each of these phases, the following equation was used:

$$Q = mV\ (h_2 - h_1) \quad (7)$$

In which:

Q: Energy needed to change curing stage for a unit of tim ($kJ*h^{-1}$)

m: Specific mass of dry air ($kgAs*m^{-3}$)

V: Volume of air to be heated in the oven per unit of time (m^3*h^{-1})

h: Air enthalpy ($kJ*kgAs^{-1}$)

The enthalpy and the specific mass of the air in the system were determined by synchrometry using the relative average ambient temperatures and moistures.

The volume of air displaced through the tobacco leaves in the oven is determined by considering the free space in the upper and lower domain areas and the space between the tobacco leaves. The ascending movement is caused mainly by the change in air density and the opening and closing of the dampers located at floor level and on the roof ridge.

The efficiency of the heat exchanger (η_1) was calculated by establishing the ratio between the energy delivered to the environment by the heat exchanger through natural convection (**Table 8**) and the total energy generated in the coal-burning heater (**Table 6**).

The amount of energy used for heating the air to the proper temperature for each of the curing phases (ε_1), was calculated as the ratio between the energy used in the initial heating of each of the curing phases (**Table 10**) with regards to the total energy generated in the burner by coal combustion (**Table 6**). The stage of maintaining the mean temperature for each curing phase ($\mathcal{E}_2$)was calculated as the ratio between the energy used to maintain the oven's mean temperature (**Table 12**) and the total energy generated by the coal burner (**Table 6**).

The amount of energy transmitted by the heat exchanger through natural convection for air heating during the air heating stage until achieving the appropriate temperature for each phase of the curing process ($\mathcal{E}_3$), was calculated as the ratio between the energy used in the initial heating of each curing phase (**Table 10**) and the energy delivered by the exchanger to the environment (**Table 8**). The stage of maintaining the mean temperature for each curing phase ($\mathcal{E}_4$), was calculated as the ratio between the energy used to maintain the oven's mean temperature (**Table 12**) and the energy delivered to the environment by the exchanger (**Table 8**).

3. RESULTS

3.1. Temperature behavior on heat exchanger surface

Figures 2 and **3** show the curves for temperature behavior at the different measurement points (**Figure 1**) in oven no. 1 on farm 3. In these figures, we can observe the high variability of the exchanger's surface temperatures throughout the different curing stages, showing the difficulty of generating stable domain temperature conditions in this system. We can also observe the effect of discontinuous fuel feeding with high temperature spikes when fuel is fed into the burner and considerable temperature reductions when fuel is not added at the correct moment, even going out at times, which can cause serious damage to the product.

Table 1 shows the average temperature achieved at each of the measurement points for each of the curing process stages. This information is used to calculate the efficiency of fuel use in the heat exchanger.

Figure 1. Plan view of traditional tobacco oven with location of surface temperature measurement points.

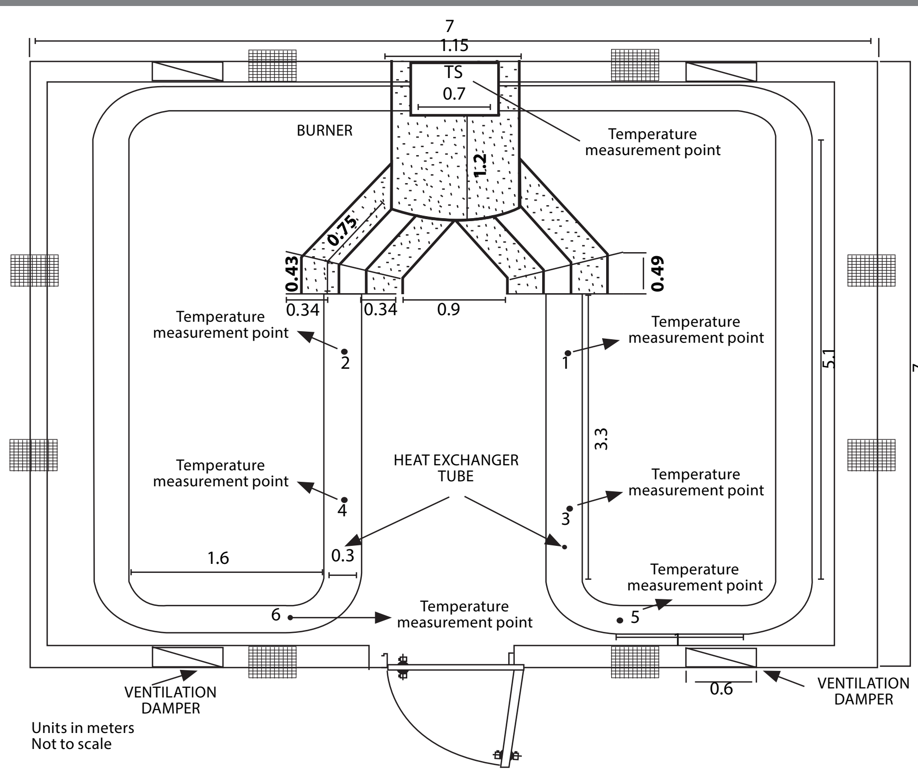

Figure 2. Heat exchanger surface temperature behavior over time at measurement point 1, oven no. 1, farm 3.

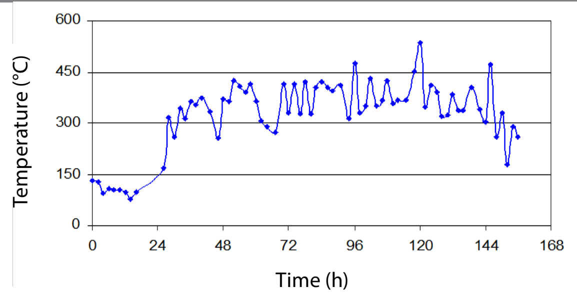

Figure 3. Heat exchanger surface temperature behavior over time at measurement point 3, oven no. 1, farm 3.

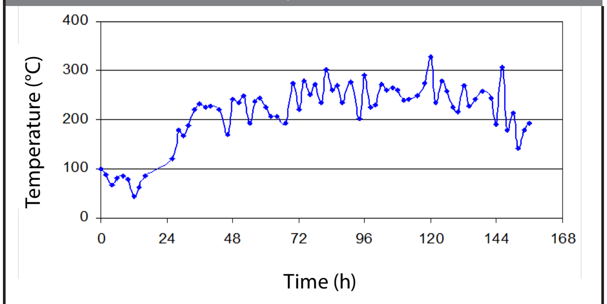

Table 1. Average temperatures at heat exchanger measurement points for each phase of the curing phase in oven no. 1, farm 3

Measurement Points	Average Temperatures at Exchanger Measurement Points °C		
	Yellowing	Color Fixation	Vein Drying
TS	106	217	243
1	104	308	366
2	107	305	361
3	77	196	241
4	85	218	270
5	82	168	208
6	89	213	262

The temperature measurements at the different points along the heat exchanger allow us to observe that the temperature decreases the farther the points are from the burner with high temperatures at the beginning of the tube, points 1 and 2 (**Figure 1**), and lower temperatures at points 5 and 6. The decrease in temperature from the burner outlet (mean value of measurement points 1 and 2) and the more distant measurement points (mean value of measurement points 5 and 6) at each of the curing stages was the following: 11.5ºC for yellowing, 81.5ºC for color fixation, and 95.5ºC for vein drying.

At the equidistant measurement points on each of the exchanger's lines, we observed temperature differences which are reflected in non-uniform heating of the tobacco leaves (**Figure 1**).

3.2. Behavior of environmental conditions in the curing oven's interior

Figure 4 shows the behavior of the dry-bulb and wet-bulb temperatures. Here we can see the constant temperature variation in the oven's interior. This reflects the influence of adding fuel to the burner among the curing variables.

For the ovens evaluated, the average temperature for each of the stages is close to the patterns recommended by tobacco companies (SENA, 2005) as can be observed in **Table 2**. In practice, however, we find maximum and minimum temperature spikes that differ greatly from the value indicated (**Table 3**).

3.3. Patterns

Temperatures suggested by production companies for each of the tobacco curing stages (SENA, 2005)

Oven no. 5 at farm 1 and ovens no. 4 and no. 5 at farm 3 showed the highest temperatures during all the tobacco curing stages, exceeding the recommended temperature limits especially during the yellowing and vein drying stages. We can see this reflected in a reduction of quality in the final product. To cite on example, in oven no. 2 on farm 1, the dry-bulb temperature exceeded the 71°C suggested for the vein drying stage, reaching 88°C.

3.4. Curing time

Table 4 shows the variation in the time used for each of the curing stages in the batteries of ovens evaluated. In the color fixation phase, which should theoretically last 36 to 48 hours, there were cases in which this stage lasted only 12 to 14 hours. This reduction in color fixation times is reflected in an increase in the time used for the vein drying stage: up to 122 hours when the recommended time is 40 to 60 hours. This leads to an extra cost for fuel use and reduced leaf quality.

Figure 4. Dry-bulb and wet-bulb temperature variations over time in oven no. 1, farm 3

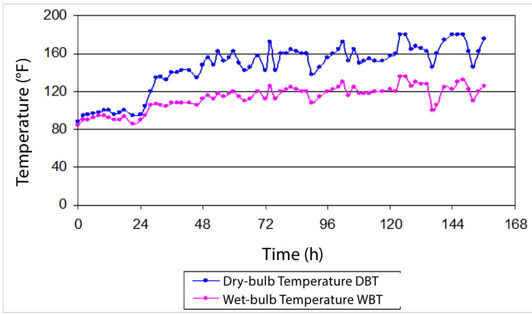

Table 2. Average dry-bulb temperature in ovens evaluated

Farm	Oven	Average Dry-bulb Temperature (°C)		
		Yellowing	Color fixation	Vein drying
1	2	38	54	67
	5	39	57	72
2	1	33	55	68
	2	34	54	70
3	0	36	44	67
	1	36	56	71
	3	37	56	72
	4	39	54	73
	5	38	52	73
Average		**37**	**54**	**70**
Patterns		**38**	**60**	**71**

The yellowing stage cannot be analyzed in the same way given that it is sometimes completed at ambient temperature and with the ventilation dampers closed for several days. This procedure has a direct impact on this stage because it does not use thermal energy from the heat exchanger during a part of this period.

Table 4. Time used in each stage of the curing process

Farm	Oven	Time Used per Stage (h)		
		Yellowing	Color Fixation	Vein Drying
1	2	20	28	46
	5	16	26	43
2	1	13	36	54
	2	67	51	49
3	0	20	12	121
	1	24	22	110
	3	48	22	122
	4	26	22	104
	5	16	14	93

3.5. Fuel consumption and energy generated by the burner in the curing stages

Table 5 shows the average fuel consumption for each phase of the tobacco curing process.

Table 3. Minimum and maximum dry-bulb temperatures in the ovens evaluated

Farm	Oven	Minimum and Maximum Dry-bulb Temperatures (°C)					
		Yellowing		Color Fixation		Vein Drying	
		Tmin	Tmax	Tmin	Tmax	Tmin	Tmax
1	2	34	44	52	62	48	88
	5	33	39	46	62	51	81
2	1	31	33	45	61	61	74
	2	30	43	43	62	63	78
3	0	32	38	39	56	54	82
	1	31	38	40	61	59	82
	3	34	40	40	66	62	82
	4	36	41	43	62	58	82
	5	34	41	42	61	54	87

Table 5. Average coal consumption in the curing phases

Phase	Coal Consumption ($kgx*h^{-1}$)
Yellowing	7
Color Fixation	12
Vein Drying	18

In order to determine the energy produced by the burner during each phase, we considered the calorific value of the coal used in the study area and the average amount of fuel used during each of phase of the curing process (**Table 6**).

Table 6. Energy generated (Qt)) by the burning of coal in the burner$^{\phi}$

Phase	Q_t ($MJ*h^{-1}$)
Yellowing	207
Color Fixation	354
Vein Drying	532

$^{\phi}$ Calorific value of coal 29.56 $MJ*kg^{-1}$ (Ingeominas, 2005).

3.6. Calculation of energy delivered to the oven's interior environment by the heat exchanger through natural convection

In order to calculate the energy delivered to the environment by the heat exchanger, we used **Equations 1** through **5.** The average surface temperature (T_w) and average environment temperature (T_∞) were obtained from the readings taken at the measurement points on the heat exchanger and the oven's interior environment during the three stages of the curing process. **Table 7** shows these values:

Table 7. Average heat exchanger surface temperatures and average temperature in the oven's interior for each of the curing stages

Temperatures (ºC)	Yellowing	Color Fixation	Vein Drying
T_w	85	156	199
T_∞	37	54	70

The values calculated for the heat transferred by the heat exchanger during the yellowing, color fixation, and vein drying stages are presented in **Table 8**.

Table 8. Energy delivered to the oven's interior environment by the heat exchanger in the different curing stages

Phase	Q (W)
Yellowing	4325
Color Fixation	13200
Vein Drying	17236

3.7. Calculation of the energy used to begin each curing phase and the energy needed to maintain the average temperature in the internal environment

The energy needed to heat the domain environment at the beginning of each curing phase was calculated with **Equation 6** using the average environment temperatures (**Table 7**) and the relative average moistures shown in **Table 9.**

Table 10 shows the amount of energy needed to change from one curing phase to another.

Table 9. Relative average moisture for each curing stage

Phase	RM (%)
Yellowing	78
Color Fixation	55
Vein Drying	39

Table 10. Energy needed to heat the air when changing curing phases

Phase	Q_f ($kJ*h^{-1}$)
Yellowing	10025
Color Fixation	13542
Vein Drying	14014

The energy needed to maintain the temperature and relative moisture conditions at a mean value, considering the variation between maximums and minimums in each curing phase, was calculated using **Equation 6** with the maximum and minimum values for environment temperature and relative moisture shown in **Table 11**.

Table 11. Maximum and minimum values for environment temperature and relative moisture for each curing stage

Phase	T (ºC)		HR (%)	
	Minimum	Maximum	Minimum	Maximum
Yellowing	33	40	63	89
Color Fixation	43	61	44	77
Vein Drying	57	85	25	55

Table 12 shows the values calculated for the energy needed to maintain the average temperature in the internal environment for each phase of the curing process.

Table 12. Energy needed to maintain average temperatures in the oven's internal environment during the phases of the tobacco curing process

Phase	Q_m (kJ*h^{-1})
Yellowing	1965
Color Fixation	10247
Vein Drying	11308

3.8. Energy use efficiency in the tobacco curing process

In the analysis of fuel use efficiency, the following three conditions were considered:

3.9. Heat exchanger efficiency (η_1):

Energy delivered by the exchanger through natural convection with regards to total energy generated in the burner (**Table 13**).

Table 13. Heat exchanger efficiency for each stage of the curing process

Phase	η_1 (%)
Yellowing	7,6
Color Fixation	13,5
Vein Drying	11,7

3.10. Amount of energy used for heating the air

Amount of energy used in heating curing air to obtain temperature conditions for the beginning of each of the phases with regards to the total energy produced by the burner ($\mathcal{E}_1$), and the amount of energy used to maintain the mean curing air temperature during each of the phases of the curing process with regards to the total energy produced by the burner ($\mathcal{E}_2$), **Table 14.**

Table 14. Percentage of energy generated the burner used for heating the air in each stage of the curing process

Phase	$\mathcal{E}_1$ (%)	$\mathcal{E}_2$ (%)
Yellowing	4,9	1,0
Color Fixation	3,8	2,9
Vein Drying	2,6	2,1

3.11. Amount of energy transmitted by the heat exchanger through natural convection

Amount of energy used in heating the curing air in order to obtain temperature conditions for beginning each of the phases with regards to the energy delivered to the environment by the exchanger ($\mathcal{E}_3$) and the amount of energy used to maintain the mean curing air temperature during each of the phases of the curing process with regards to the energy delivered to the environment by the exchanger ($\mathcal{E}_4$), **Table 15**.

Table 15. Percentage of energy transmitted by the heat exchanger through natural convection used for each stage of the curing process

Phase	$\mathcal{E}_3$ (%)	$\mathcal{E}_4$ (%)
Yellowing	64,4	12,6
Color Fixation	28,5	21,6
Vein Drying	22,6	18,2

As can be observed in **Tables 13**, **14**, and **15**, the use efficiency of the energy generated by the fuel is very low due especially to the fact that heat transfer is done through natural convection. This has two effects on the process: one of them is the low use of energy, and the other is the difficulty of transporting the hot air through the tobacco leaf from the lower to the upper section of the mass of tobacco, causing the problems of non-uniformity in curing mentioned above.

4. CONCLUSIONS

- In traditional ovens, the heat transfer system is natural convection with the use of internal tubes that are heated with the combustion gases from the burner. This method is quite inefficient, difficult to control, and also generates a fire hazard due to the possibility that the tobacco leaf may fall on the tubes, which sometimes reach “red hot” conditions.

- The temperature variability along the surface of the heat exchanger during the different curing stages shows the difficulty of generating stable temperature conditions in the domain for this kind of system.

- The environmental conditions in the oven’s interior are directly affected by the use of the curing oven’s natural ventilation dampers, which is governed more by personal judgment than a standardized process. They are also affected by discontinuous fuel addition, which causes spikes in temperature and relative moisture. This reflects the influence that this type of fuel supply has on the curing variables.

- In the ovens evaluated, the average temperature in the internal environment used for each stage is close to the patterns recommended by tobacco production companies. However, there are peaks and valleys that differ significantly from the pattern value.

- In general, the times used for the different stages of the curing process do not correspond to those suggested by tobacco companies, which generates unfavorable conditions during the process and an excessive use of fuel.

- The use efficiency of the energy generated by the fuel is very low due especially to the fact that natural convection is used for heat transfer. This has two effects on the process: one is the low use of energy, and the other is the difficulty of transporting hot air through the tobacco leaf from the lower to the upper sections, causing non-uniformity in the curing process.

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