CONCURRENT WOODBURNING FURNACE FOR GRAIN DRYING

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Abstract. *It has been shown that the grain drying process accounts for most of the energy expenditure along grains post-harvest . Most of the Brazilian drying mills use counter-current flow woodburning furnaces to produce warm air near 100 ºC. Warm air generated in such furnaces contains high amounts of tar, carbon monoxide, soot and particulate matter which negatively affects the grain quality. Incandescent particulates also presents high risks of fire ignition inside the dryers. Furthermore those furnaces are difficult to control the delivery of the proper air temperature. This work presents an exploratory study of a concurrent flow furnace design to meet thermal energy needs for dryers while meeting air drying quality standards. It is an alternative design for furnaces used for grain drying. A 40kW power furnace was built to investigate the influence of three different grate areas and wood feeding regimes. The furnace operated under natural and induced draft. It all led to eighteen different experiment set-ups. In each test, carbon monoxide concentration and temperature of the flue gas were monitored. We also observed operational issues. Results showed that concurrent wood burning furnaces can be very succesfull in providing low levels of carbon monoxide, of tars and of soot as well. It also showed near constant temperature levels of drying air. Energywise, the average perfomance of the furnace was around 75% with the original design.*

Keywords*: woodburning, concurrent,downdraft, grain drying.*

1. INTRODUCTION

Grain drying is of paramount importance along the post-harvest chain. The proper drying of grains, mainly soybeans and corn beans in Brazil, warrants the grains long-term storage with little loss of quality (e.g. Lorini *et.al*, 2002).

Almost all thermal energy expenditure in the post-harvest takes place in dryers. Dryers are combined with hot air generators in which fuel is burnt. Most of Brazilian drying mills make use of counter-current flow woodburning furnaces to produce air near 100ºC. In such furnaces wood is fed through windows and are stacked over the grate. On one hand, energy from wood is renewable and may be sustainable with proper management. On the other hand, such furnaces usually led to incomplete combustion. Exhaust gases thus contain significant amounts of carbon monoxide, soot and particulate matter, as well as tar. Tar is harmful to the quality of the grains, while soot and incandescent particulate can trigger fire inside the dryer (e.g. Lorini et.al, 2002). To overcome such problems, conventional dryer furnaces make use of auxiliary equipments and multiple combustion chambers.

In this paper we present an alternative design for grains dryers. We designed, built and tested a concurrent flow wood burning furnace. Primary combustion air flows downwards and so does the flame. We tested the furnace in three different feeding regimes and grate areas, and we also ran the tests under natural draft and induced draft. Results showed that the concurrent flow furnaces can overcome high CO and tar contents, and also decrease the risk of trigging fire in the dryer with simple geometry and no auxiliary equipments. In addition , temperatures of exhaust gases varied in a narrow range.

2. COUNTER-CURRENT FLOW AND CONCURRENT FLOW WOODBURNING FURNACES

In short, counter-current furnaces are fed from the top of the grate while air from below. Air firstly meets burning char, where most of the oxygen are consumed. Usually a secondary air intake is then necessary in the combustion chamber. Otherwise combustion would take place with oxygen deficit. Figure 1 illustrates the main features of conventional furnaces (counter-current).

The combustion worsens when newly fed wood on the upper layers is swept by hot gases. That leads to higher rate of pyrolysis and volatization under little or no oxygen.. Ultimately that would produce tar, and high concentration of soot and CO. The complexity of the design of the counter-current furnace is also illustrated in Fig. 1. One can notice a secondary air inlet, on a three-staged combustion chamber with zigzag flow barriers to break up the flame and also to function as inertial precipitators. A cyclonic device is also installed to ensure that almost no incandescent particulate are drawn into the dryer.

It is not an easy task to design a combustion chamber that provides the necessary oxygen throughout the entire feeding cycle (for the most common furnaces). Even though, the knowledge of counter-current flow is widespread and century old (e.g. Nogueira e Lora, 2003). In sum, counter-current flow furnaces for dryers in Brazil are limited by high installation costs and yet they do not provide good quality drying air.

In downdraft woodburning furnaces air flows concurrently with the fuel, and flames do not occur within the interstices of the wood stack. Flames are formed mostly in the lower layer and flows downward. Such feature prevents heating the upper and newly fed fuel to ignition or to start pyrolysis. Thus, the volatization takes place in a moderate pace. A schematic view of a concurrent flow furnace is shown in Fig. 2. For grain drying purposes, the geometry becomes rather simpler than the counter–current furnace shown in Fig. 1

That is possible due to the low pace volatization combined with enough oxygen and combustion conditions in the so called adiabatic zone. In this zone, temperature reaches its peak and residence time can be dramatically reduced, even with simple geometries (e.g. Borges, 1994). A main resulting feature is the clean exhaust gases with no soot neither incandescent particulate. Therefore there is no longer need of secondary combustion chambers and precipitators to control the risk of fire in the dryer.

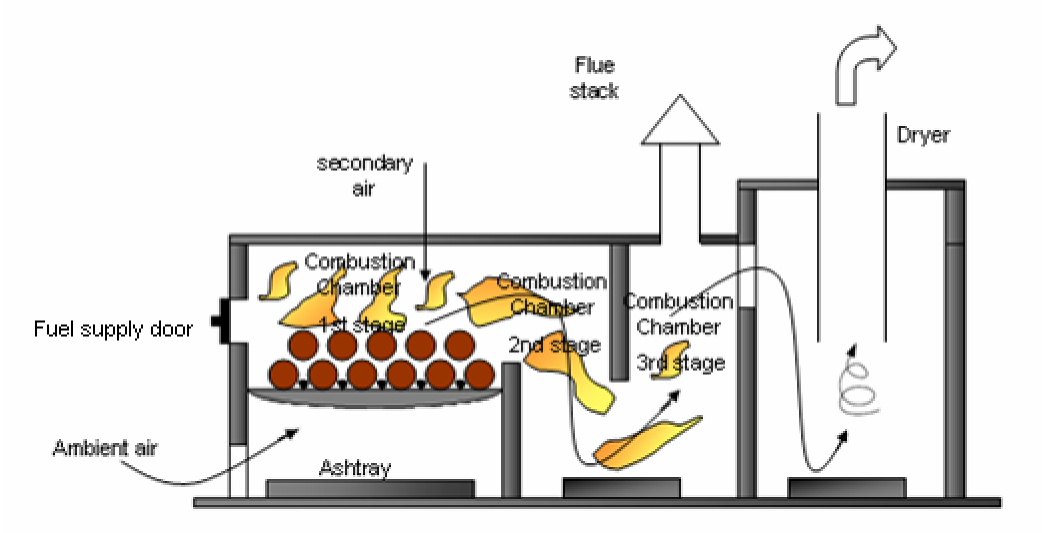

Figure 1. Counter-current flow design for grain dryers

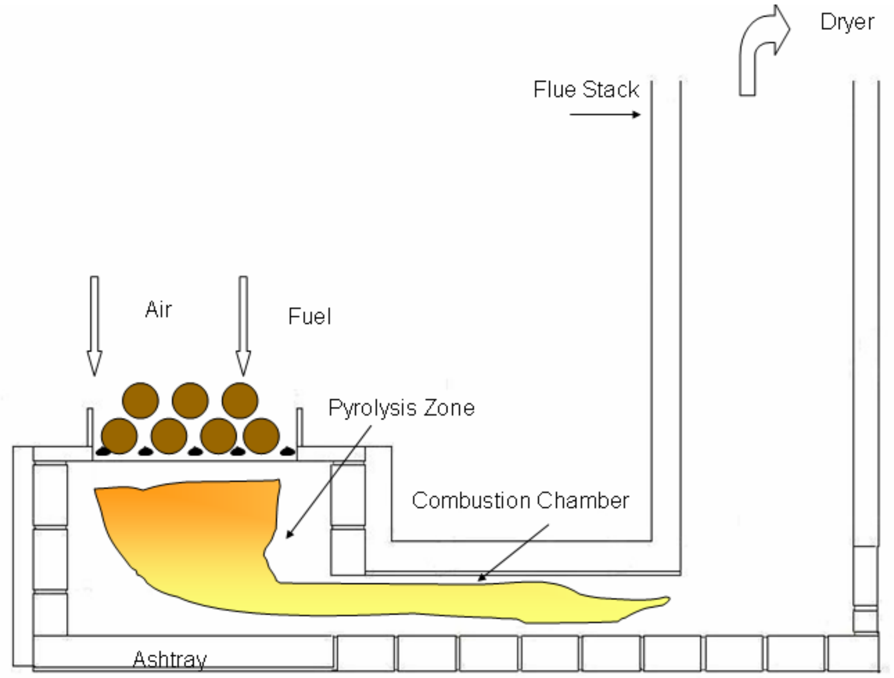

Figure 2. Concurrent flow design for grain dryers

Concurrent flow furnaces have been subject of earlier studies. For instance, Verhaart (1990) built a small prototype downdraft furnace that produced carbon monoxide levels around 300 ppm.

Another interesting work (Borges, 1994) explored the possibility of downdraft combustion for domestic wood stove. The carbon monoxide level was near 1600 ppm.

Silva (1998) studied a vegetable char furnace to dry coffee beans. Although not mentioned in the paper, it seems that such furnace operated in downdraft flow. The performance was not satisfactory, probably because that almost no volatilization or pyrolysis take place in char. It seems that the research group has not continued that line of work.

Nussbaumer (2003) analyzed experimentally the combustion in a downdraft furnace in two stages. The first stage, where pyrolysis took place, operated with insufficient air. The combustion of gases took place in the second stage under high excess air. The author obtained very low concentrations of CO and C_xH_y (O_2 @ 10%).

Overall downdraft furnaces can yield almost the same thermal performance, be less costly, since it can be more compact and require less auxiliary equipments. And most of all, it can yield drying air with little tar and carbon monoxide, as well as almost no soot and incandescent matter. Ultimately downdraft furnaces can deliver near constant temperature that contributes to good quality drying.

3. METHODS AND MATERIALS

The work presented in this paper is the first step in the quest for knowledge to design a full scale furnace for grain dryers to Brazilian agroindustry.

We devised an exploratory study of downdraft combustion. First we built a prototype inspired on previous works, such as Verhaart (1990) and Borges (1994). Then we devised a test plan: we observed thermal performance, carbon monoxide levels and temperature variation in time. We controlled the feeding regime and utilized different grate areas. We tested the prototype under natural draft and induced draft. Data were then verified and consolidated in tables and charts.

3.1. Prototype

We designed and built a downdraft furnace to yield nearly 40kW at the top of the insulated flue stack. The main features of the prototype are shown in fig. 3 and fig. 4. One can notice two distinctive sections, namely the pyrolysis or volatization which is broad and squared and the combustion chamber (adiabatic zone) which is flat and long. No moving parts were installed. Wood logs were fed by the top. The grate was placed on the top of the pyrolysis zone.

The furnace was built in commercial refractory bricks and plates. Inside walls of the combustion chamber were lined with ceramic fiber paper as the first insulation layer. Outside walls were covered with ceramic fiber insulation and aluminum foil.

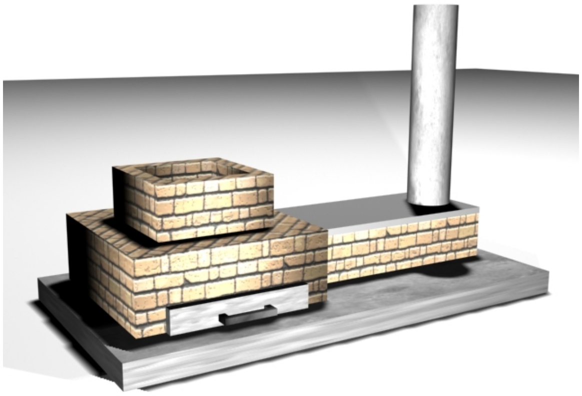

Figure 3 . Electronic model of the concurrent flow furnace

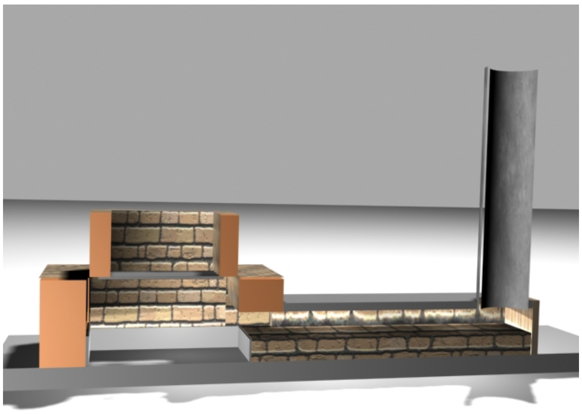

Figure 4. Electronic model showing inside features of the concurrent flow furnace

Two flue stacks were used: one for natural draft (1m long and 0.18 m diameter) and one for induced draft (diameter of 0.30 m and 1.5 m of height). Figure 5 shows a picture of the furnace with no external insulation. Figure 6 shows a picture of the duct connection in the grain dryer. Induced draft for our experiment was driven by the suction generated by the exhaust fan of the dryer .

3.2. Fuel

We utilized Eucalyptus logs. Logs were cut into 0.12 cm × 0.02 cm pieces. We considered a typical elementary composition, namely 52% of carbon (C), 41% oxygen (O), 6% of hydrogen (H), and 1% of ash (Z), (Sulitato, 1985).

Moist contents were measured in an oven near ± 103 ºC. In average, water content was near 13.5% dry basis and 12% wet basis.

Figure 5. Natural draft furnace with no external insulation

Figure 6. Induced draft furnace connected to the dryer

3.3. Experimental plan

This is an exploratory research, therefore we chose to use a factorial combination of two parameters in three levels, in addition to two different draft conditions. We used three different grate sizes and three different wood feeding regimes. That led to 18 different experimental tests.

In all tests the fuel was sorted in pre-weighted loads and then were fed in the selected paces. Therefore the rate of combustion was not measured during the tests.

The combination of the great size and the feeding rate leads to the known parameter loading rate, measured in $kg/m^2.h$.

3.4. Instrumentation

Instruments were placed to provide necessary data for the energy balance, to estimate energy performance and atmospheric emissions.

Fuel loads were weighted in hook-type scale (KERN model CH15K20). The range of the scale was up to 15 kg, with an error of 10g.

Temperature measurements were performed by thermocouples of type K and S. They were all connected to a data logging system, namely National Instruments cFP 2020.

Carbon monoxide and oxygen concentrations were directed measured by a gas analyzer model TEC-GA12, manufactured by MADUR. The sensor operates under electrochemical principles. Oxygen was read in volumetric percentile with 0.01% precision, while carbon monoxide was read in volumetric ppm with 1 ppm precision. Other components were estimated by stoichiometric balance. In Fig. 7 is shown a schematic view of the placements of temperatures sensors and the gas analyzer probe.

Thermocouples labeled as number 1 and 2 are the ones of S-type. The other ones are K-type. The temperature measured at point "0" was used to estimate the useful power.

3.5. Efficiency

The furnace efficiency was estimated according to the first principle of Thermodynamics. It was defined as the ratio between useful enthalpy of the exhaust gases (at point 0) an the nominal energy load (Eq 1).

$$\eta = \frac{Q_{\text{useful}}}{Q_{\text{nominal}}} \qquad (\%) \qquad (1)$$

The average useful energy, $\overline{\dot{Q}}_{\text{useful}}$ is calculated by Eq. 2, while the nominal energy load from the fuel can be determined by Eq. (3). The mass flow rate of exhaust gases was estimated by the stoichiometric balance.

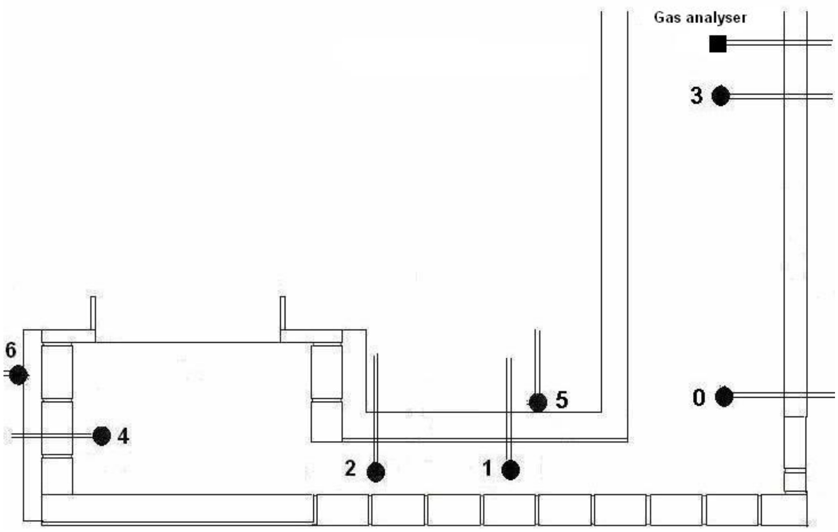

Figure 7. Location of thermocouples and of the analyzer probe

$$\overline{\dot{Q}}_{\text{useful}} = \overline{\dot{m}}_{\text{comb\_gas}} \overline{\Delta h}_{\text{comb\_gas}} \quad \text{(kW)} \tag{2}$$

$$\overline{\dot{Q}}_{\text{nominal}} = \overline{\dot{m}}_{\text{wood}} LHV_{\text{wood}} \quad \text{(kW)} \tag{3}$$

Where:

$\overline{\dot{m}}_{\text{comb\_gas}}$: time average mass flow rate of the combustion gases (kg/s);

$\overline{\Delta h}_{\text{comb\_gas}}$: time average enthalpy variation of the combustion gases (kJ/kg).

$\overline{\dot{m}}_{\text{wood}}$: averaged wood feeding regime on average (kg/s);

LHV_{wood} : wood lower heating value (kJ/kg).

Each test took approximately a day long. Half-day to weight logs and to do all pre test check-up.

The average lower heat value of wood used was 16000 kJ / kg, calculated according to the composition of the wood. The enthalpy of flue gas was calculated based in thermodynamics tables (e.g Van Wylen, 1998). It was used a temperature reference of 25 °C.

4. RESULTS

4.1. Flow regime

In all tests the concurrent (downdraft) flow took place. Figure 8 shows a picture from the top of the grate with the log stack. One can notice that flame occurs only underneath the logs, and also that the upper faces of the logs have not pyrolysed yet. In fact, the upper layer is only undergoing drying process.

4.2. Efficiency

The results of the eighteen tests are summarized in Tab.1. The first column indicates the test number, the second column the grate area (G_a), the third column the feeding regime (F_{wood}) and the fourth column the type of draft. The column labeled as period (Δt) shows for how long the valid operation regime took place. The next column shows the flue gas mean temperature during the valid regime period (thermocouple "0"). The average carbon monoxide concentration is shown in the next column, and the next one show the concentration of carbon monoxide corrected for reference, 11% of O_2. The tar concentration (C_xH_y) is presented in the next column. Followed by the air excess (E), obtained on the tests. The efficiency is presented in the last column.

Figure 8 . Illustration of flame showing the concurrent flow.

According to the IAP (Environmental Agency of State of Parana) resolution 054/06, the value of the oxygen of reference for fuels derived from wood is 11%.

Table 1. Results of the experimental tests

Test	G_a (m^2)	F_{wood} (kg/min)	Draft	Δt (min)	T (ºC)	CO (ppm)	CO (ppm) - 11% O_2	C_xH_y (ppm)	E	η (%)
1	0,13	0.125	Natural	17	786	131	120	33	1.93	75.2
2	0.13	0.133	Natural	36	817	116	102	29	1.85	75.6
3	0.13	0.150	Natural	67	840	85	73	21	1.80	76.2
4	0.08	0.125	Natural	30	811	120	106	30	1.85	76.1
5	0.08	0.150	Natural	55	830	88	72	22	1.71	72.3
6	0.08	0.133	Natural	42	770	171	147	43	1.81	74.8
7	0.05	0.150	Natural	32	804	112	91	28	1.71	70.2
8	0.05	0.133	Natural	31	874	73	60	18	1.74	77.8
9	0.05	0.125	Natural	50	817	105	89	26	1.78	73.6
10	0.05	0.150	Induced	30	590	652	968	163	3.10	82.8
11	0.05	0.133	Induced	75	500	968	1761	242	3.79	75.0
12	0.05	0.125	Induced	60	402	1147	2558	287	4.60	80.3
13	0.08	0.125	Induced	92	395	1195	2756	299	4.78	71.5
14	0.08	0.133	Induced	80	415	1135	2208	284	4.04	64.7
15	0.08	0.150	Induced	100	490	903	1480	226	3.42	75.5
16	0.13	0.125	Induced	60	345	1189	3121	297	5.42	77.7
17	0.13	0.133	Induced	90	365	1175	2701	294	4.77	73.5
18	0.13	0.150	Induced	97	410	1162	2515	291	4.48	79.8

Tests 1 to 9 ran under natural draft. The average temperature of those tests was higher then 820ºC, and the time averaged concentration of CO was near 100 ppm. In the induced draft tests the average temperature was about 430ºC with 1200 ppm carbon monoxide. The air excess (E), that describes the ratio between the locally available and the stoichiometric amount of combustion air, was too high in the induced draft tests.

Energy balance was performed in order to verify whether data and analyses were consistent. In the natural draft tests (1 to 9) the energy imbalance was 7% on average, while in induced draft tests (10 to 18) the average imbalance was 15%. It is likely that the imbalance was larger in the induced draft tests because the method to estimate the exhaust gas flow rate was based on stoichiometric balance, rather than be directly measured.

Energy losses by the furnace walls were larger in tests with natural draft, while chemical losses were larger in induced draft tests. Nevertheless chemical losses were numerically insignificant when compared to walls losses.

Thermal efficiencies of the tests were calculated by Eq. (1). The average efficiency of the natural draft tests was 74%, and the average efficiency in the induced draft tests was near 74% as well. In induced draft tests, efficiencies varied from 64% to 83%, whereas the efficiencies under natural draft were within 70% and 78%.

An overall comparison of performance between natural draft and induced draft operation needs further tests since the energy imbalance of induced draft was twice larger than the imbalance of the natural draft. Therefore a preliminary performance comparison should be carried out based on exhaust gases temperature, walls losses and carbon monoxide emissions.

Following this line of thought, natural draft tests are likely to have performed better, since they resulted in very low CO emissions (ten to twenty times lower) and temperatures above 700ºC.

Induced draft tests were expected to perform better than natural draft ones. However, due to the minimum draft possible to set in the whole apparatus, air intake was still excessive for the experimental conditions planned.

Table 2. Data of energy balance

	Natural Draft (test 8)	**Induced Draft (test 11)**
Losses by walls (kW)	7.3	4.0
Chemical losses (CO) (kW)	2×10^{-5}	4×10^{-5}

The best loading rate observed was on test number 8, namely at 160 kg/m^2.h (highest efficieny with lowest CO). This figure is 50% higher than the 110 kg/m^2.h reference for counter-current furnaces (Bazzo, 1995). That indicates a potential furnace size reduction for the same power level.

Thus we estimated tar contents (C_xH_y) by means of an indirect relation presented by Busmann (1988). Therefore, in all natural draft tests, tar levels were around 40 ppm. A previous work reported 780 ppm in conventional furnaces (Oanh *et al* ,1999).

Since the induced draft could not be proper set for the feeding regime planned, we performed an extra test in which the feeding regime was selected for proper operation. We doubled the largest feeding regime to 0.3 kg / min. The temperature rose to 930ºC with a standard deviation of 16ºC for a 90 minutes period (Fig. 9). It also resulted in a CO levels of 73 ppm with 9 ppm of standard deviation (Fig.10). Efficiency also increased and exceeded 85%. Useful power was twice as much as the power of the best test, reaching 70kW. The loading rate was 140 kg/h.m^2.

In all tests the exhaust gases were visually clear and colorless, and no incandescent particle was observed.

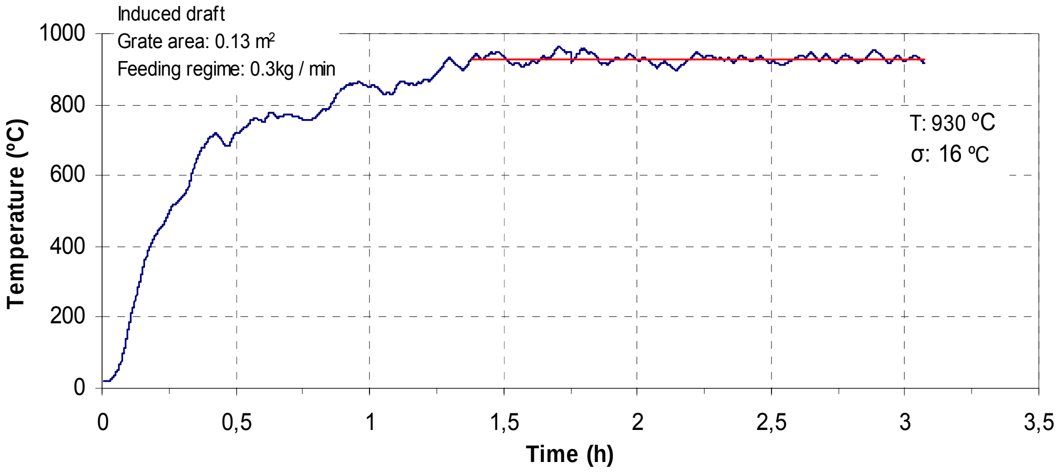

Figure 9 . Temperature variation on the exploratory test

5. CONCLUSION

In this paper, a experimental study of concurrent flow, or downdraft, woodburning furnace was carried out. The results of nineteen tests representing a combination of different grate sizes, feeding regimes and draft conditions, showed that: low CO and tar emission levels can be achieved, that almost no particulate or soot was produced, and that the furnace can operate at high levels of temperature with narrow range of variation. Furthermore, the downdraft furnace design and construction were simple when compared to a counter-current flow furnace for the same performance regarding grain drying.

The prototype furnace also shown to be easy-operated.

Design parameters were based on a counter-current flow furnace for a nominal power of 40kW. The downdraft furnace, however, achieved 70 kW net thermal power. That indicates a potential size reduction. Overall, the downdraft furnace shows potential to be less costly (installation, operation and maintenance) than the conventional grain-dryers furnaces.

In sum, concurrent flow furnace presents great potential as source of thermal energy for grain dryers.

Design and operational regime can still be optimized since the prototype built was only exploratory.

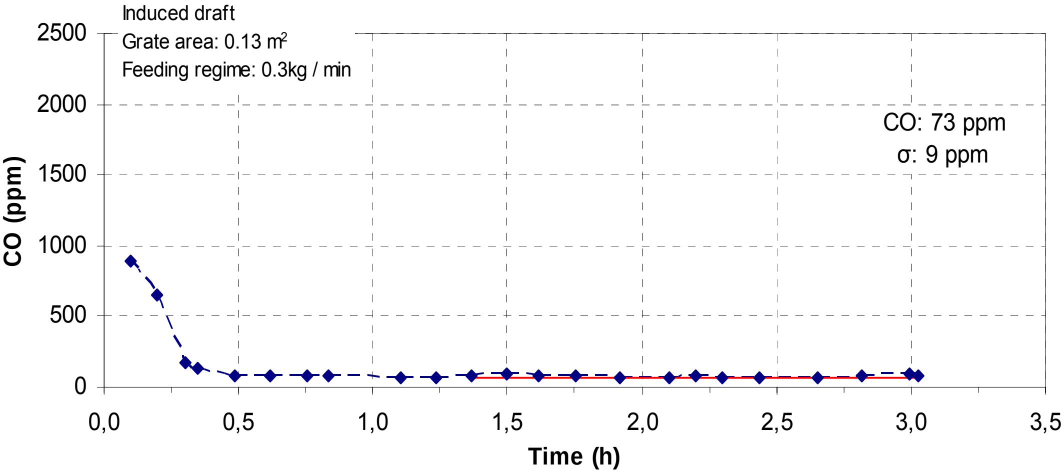

Figure 10. CO variation on the exploratory test

6. ACKNOWLEDGEMENTS

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