# *New Technologies for the Drying of Coffee*

**(Taken from '*Hygienic Coffee Drying*' prepared for this resource by Juarez de Sousa and Consuelo Domenici Roberto, University of Viçosa, Brazil[1])**

## 1. Introduction:

Due to their high moisture content at harvest, 60 to 70% w.b., natural ripe coffee cherries do not flow easily in handling equipment (e.g. gravity spouts, hoppers, bucket elevators, augers) and conventional mechanical dryers. Conventional drum-type rotary dryers are an alternative, but they are generally criticised for having air-flow problems and low energy efficiency. As a result of this, the typical coffee drying process in Brazil consists of two different drying stages.

In the first stage, freshly harvested whole coffee cherries are spread on paved terraces where they are allowed to dry under the sun until they reach 35 to 30% moisture content, whereas in the second stage the coffee is dried in high-temperature mechanical dryers down to about 13% w.b.

Modifications in the drawing and the handling of the drum-type rotary dryer, accomplished by researchers from Universidade Federal de Viçosa (UFV), Brazil, show that the above-mentioned problems may be easily solved, and can transform the rotary dryer into suitable equipment to work with natural, cherry, coffee.

If the climate is such that dependable sunshine is available during the harvest season, the drying process may be conducted entirely in the open air. In this case, cherries are spread out on the drying terrace after harvesting, and dried to about 13% moisture content in a single operation. Another alternative is the complete drying of whole coffee cherries in a fixed-bed dryer or in the newest system for coffee drying, the 'hybrid terrace'. The principal drawback in utilizing conventional mechanical dryers has been the fact of their being designed primarily to dry products other than coffee, and their relative high cost. Despite the recent efforts to change this situation most of the commercially available dryers are still inefficient and have thus far been mainly used in large scale operations. Since 1998, the CBP&D-Café (Consórcio Brasileiro de Pesquisa e Desenvolvimento do Café), through the Universidade Federal de Viçosa, has been developing for the coffee grower drying, and storage technologies adapted for small coffee production systems, as outlined below.

Some innovative grain drying methods, generally applied to cereals and oilseeds, have been introduced into coffee drying facilities in the last few years in an effort to increase the drying capacity and the energy efficiency of conventional coffee drying installations, and at the same time to maintain high coffee quality. These methods include 'dryeration', reversed-direction-air-flow drying, concurrent-flow

[1] The views expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Food and Agriculture Organization of the United Nations.

and counter-flow dryers. Several other high-temperature, continuous-flow drying systems, and combination drying, that have been traditionally used to dry cereal grains to safe moisture levels for long storage periods, have been adapted to dry natural, washed, and pulped coffee (*descascado*). The main new approaches to the drying of coffee in Brazil are outlined in the following sections.

## 2. Coffee Drying in Hybrid Drying Terraces:

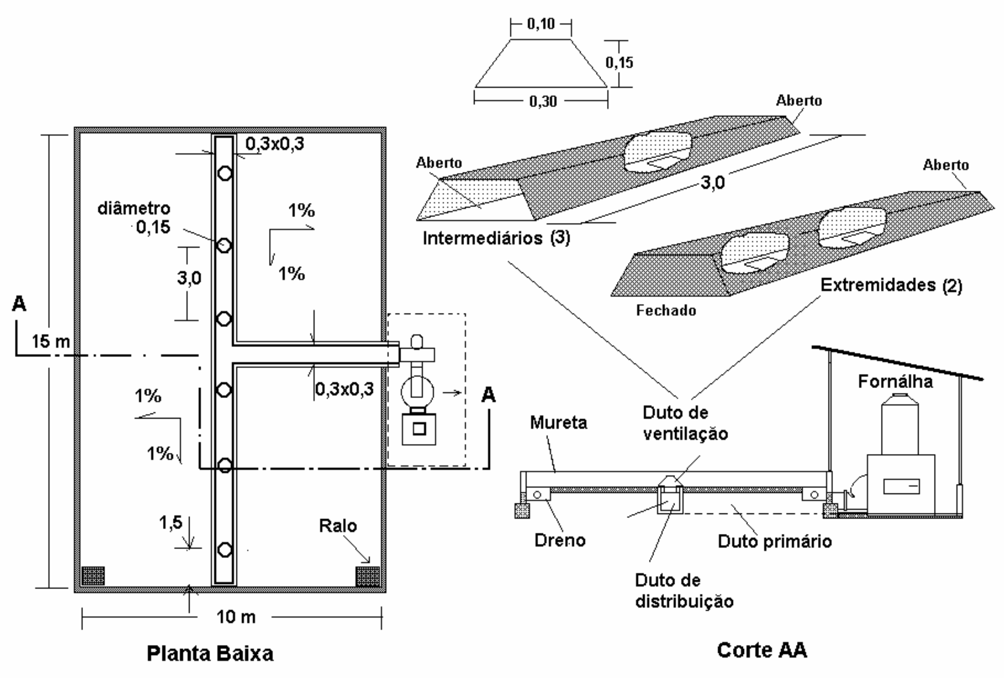
### 2.1 Design and construction of facilities

The 'hybrid terrace' is a conventional coffee drying terrace, adapted to use a ventilation system with the drying air heated by a charcoal furnace. It makes coffee drying possible in the total absence of solar radiation, during the night, and on cloudy or rainy days.

In the centre, along the length of the terrace, a sub-surface ventilation duct is installed (the main duct) with six exits for heated air. Directly above the ventilation ducts a metal aeration duct, with 23% perforated area, is placed. The coffee beans are uniformly distributed over the aeration duct to be dried with hot air in the absence of solar radiation. Arranged in this way, the terrace can be used as a conventional terrace in good drying conditions, and the furnace operated only in rainy weather, or at night time artificial drying can supplement conventional drying.

For the 150 m$^2$ drying terrace studied (7,000 litres of coffee beans), the heated drying air is forced to pass through the coffee layer by a 5 hp centrifugal fan coupled with the furnace (see Fig. 1 below).

*Fig. 1: Top and transverse view of the hybrid terrace, module of 150 m$^2$, and detail of the ventilation system.*



## 2.2 Drying operations using a hybrid terrace

As noted above, due to these changes to the drying terrace, coffee drying can be carried out continuously, using solar energy in sunny days and using heated air during the night or on rainy days. With these procedures the coffee can be dried from its initial moisture content (62% w.b.) to a final storage moisture content (12% w.b.) in less than 5 days.

From July to September, in Brazil, two hybrid drying terraces with 150 $m^2$ (or 7,000 litres capacity) were simultaneously tested for coffee drying under two different conditions.

For the first drying procedure (Hybrid Terrace 1), the drying was done using the conventional terrace drying method from 09:00 to 15:00, and using forced air heated by biomass energy from 16:00 to 08:00 the next day. For the second drying procedure (Hybrid Terrace 2), the aeration system was turned-on continuously, 24 hours a day, without the use of solar energy. The coffee layer was turned after each 3h of drying, to achieve an homogeneous moisture content. The same types of coffees were dried on a conventional drying terrace between 9:00 to 15:00 as mean of comparison.

*Coffee drying treatments:*

T1 = Pulped cherry coffee (Hybrid Terrace 2) air drying temperature at 60$^oC$
T2 = Pulped cherry coffee (Hybrid Terrace 1) air drying temperature at 60$^oC$
T3 = Natural cherry coffee (Hybrid Terrace 2) air drying temperature at 60$^oC$
T4 = Natural cherry coffee (Hybrid Terrace 1) air drying temperature at 60$^oC$
T5 = Pulped cherry coffee (Hybrid Terrace 2) air drying temperature at 40$^oC$
T6 = Pulped Cherry coffee (Hybrid Terrace 1) air drying temperature at 40$^oC$
T7 = Natural cherry coffee (Hybrid Terrace 2) air drying temperature at 40$^oC$
T8 = Natural cherry coffee (Hybrid Terrace 1) air drying temperature at 40$^oC$

T9 = Pulped cherry coffee (conventional concrete terrace) comparison test for (T1 and T5)

T10 = Pulped cherry coffee (conventional concrete terrace) comparison test for (T2 and T6)

T11 = Natural cherry coffee (conventional concrete terrace) comparison test for (T3 and T7)

T12 = Natural cherry coffee (conventional concrete terrace) comparison test for (T4 and T8)

The results show, as a function of the average drying temperature, that the time necessary to dry the coffee from treatments T1, T2, T3 and T4 were shorter than the drying times for treatments T5, T6, T7 and T8, independent of the drying system, and of the coffee type.


*Fig. 2: Setting up and operation of the hybrid drying yard in pictures:*

*a. General view of the drying terrace before the aeration ducts set up;*
*b. Details of the air exits for the aeration duct;*
*c & d. Positioning of the ducting;*
*e & f. Heaping the coffee in preparation for drying;*
*g & h. Covering the plastic cowling for operation under rainy conditions;*
*i. Operation of dryer under plastic - air flow maintaining positive pressure.*

When comparing the necessary times to dry coffee, it can be seen that the drying time needed for the hybrid drying terrace is, on average, about $^1/_5$ and $^1/_6$ of the time needed to dry natural cherry coffee and pulped coffee, respectively, using a conventional drying terrace.

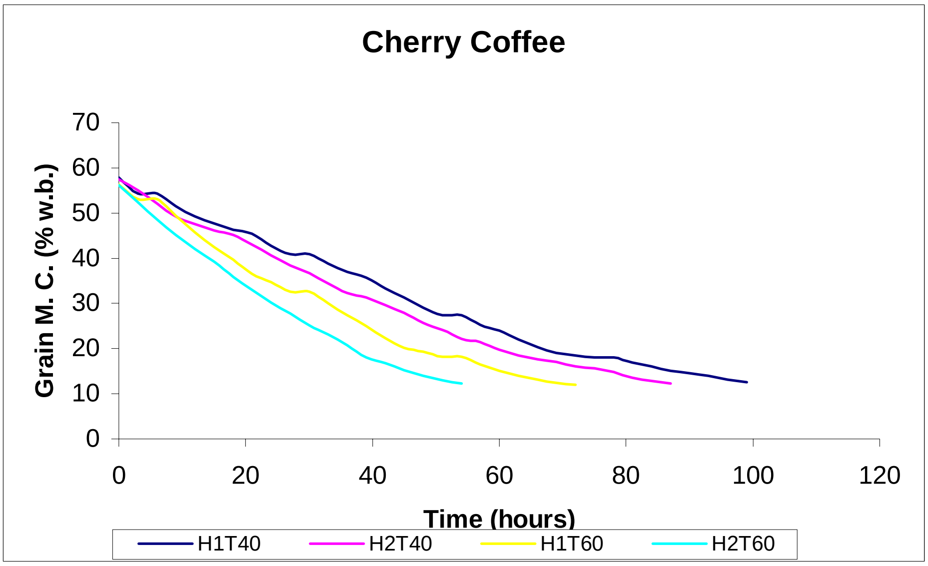



*Fig. 3:Drying curve for natural coffee cherry using terrace drying with heated air aeration system – H1 (solar + biomass energy) and H2 (only biomass energy)*

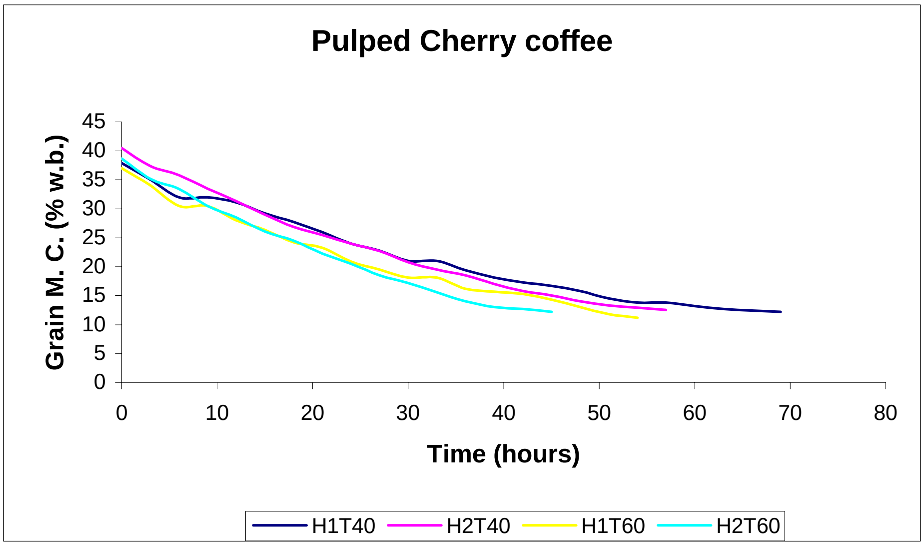



*Fig. 4: Drying curve for pulped coffee cherry using terrace drying with heated air aeration system – H1 (solar + biomass energy) and H2 (only biomass energy)*

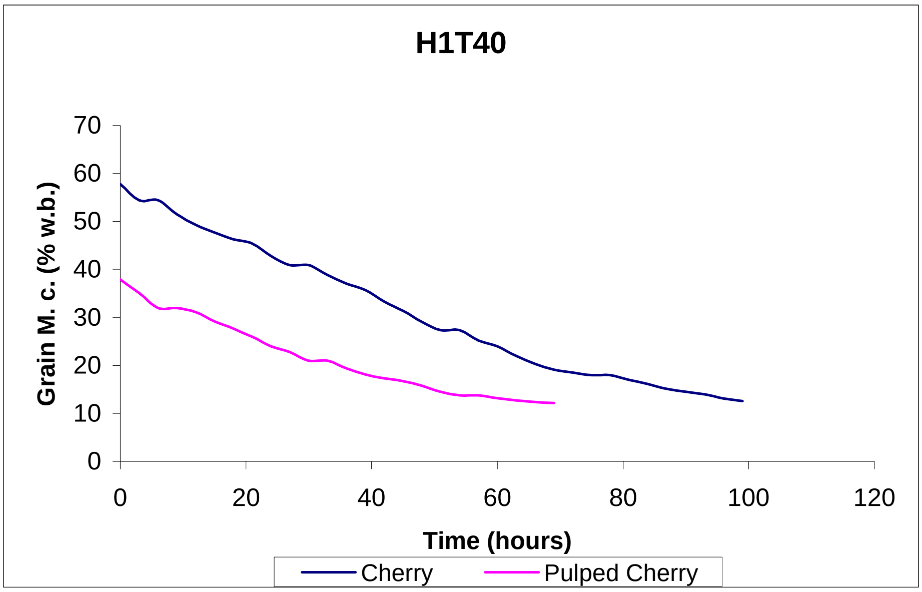



*Fig. 5: Drying curves for pulped cherry and for natural coffee cherry using drying terrace with heated air aeration system – H1 (solar + biomass energy)*

*Table 1: Cup quality and coffee beans characteristics after drying tests:*

| Treatment | Cup quality | Type | Aspect |
|---|---|---|---|
| HT2 (pulped) 60°C | Only soft | 4/5 | Good |
| HT2 (pulped) 40°C | Only soft | 4/5 | Good |
| ConvTD (pulped) | Hard | 6/7 | Good |
| HT1 (pulped) 60°C | Only soft | 4/5 | Good |
| HT1 (pulped) 40°C | Only soft | 4/5 | Good |
| ConvTD (pulped) | Hard | 6/7 | Good |
| HT2 (natural) 60°C | Hard | 5 | Good |
| HT2(natural) 40°C | Hard | 5 | Good |
| ConvTD(natural) | Hard/Rioy | 6/7 | Good |
| HT1(natural) 60°C | Hard | 5 | Good |
| HT1(natural) 40°C | Hard | 5 | Good |
| ConvTD(natural) | Hard/Rioy | 6/7 | Good |

From the results, the dried coffee beans were considered of excellent quality for the production area under conditions of 'terrace drying in the Zona da Mata, Minas Gerais'. The cup quality did not differ with the use of the drying systems (Hybrid Terraces 1 or 2) for the same coffee type. The same, however, is not true when the drying results from the Hybrid Terrace system are compared with the drying results from conventional drying terrace.

### 3. Flex Dryer:

The 'flex dryer' is a combination of the traditional fixed bed dryer (model: UFV-J2) with a solar collector. The drying air can be heated with energy from the combustion of firewood, charcoal or gas or with solar energy or with a mixture of solar energy and combustion energy. For the fact of using different sources of energy, it was named 'Flex dryer'.

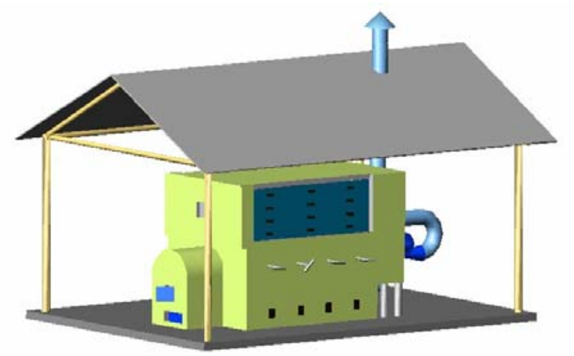


*Fig. 6a: Flex dryer with traditional roof*

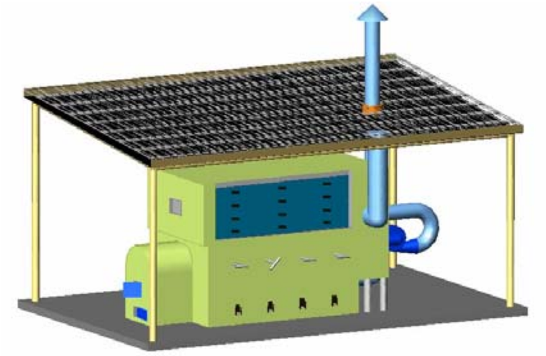


*Fig. 6b: Flex dryer with a solar roof collector*

The flex dryer incorporates both the furnace and heat exchanger of a silo dryer within a natural convection design and a solar collector, with common ducting. To complete the dryer system, a fan was added for use with deeper coffee layers where additional pressure is required to force through the hot air. In this case, the dryer works in traditional fixed bed dryer mode with indirect heating by the furnace.

Note, that in the absence of electricity, which is frequently the case with rural electricity supplies, the drying can continue using the natural convection mode. In this case, the height of the coffee layer should be reduced, or more frequent stirring is needed. Besides forcing the convection in the dryer pre-chamber, the fan is also used to draw air over the 'roof collector' channels and be pre-heated by solar energy. The use of the complementary solar energy, besides reducing substantially the consumption of other fuels, is that it is non-pollutant, and the 'roof collector' design is just a little more expensive than a standard roof.

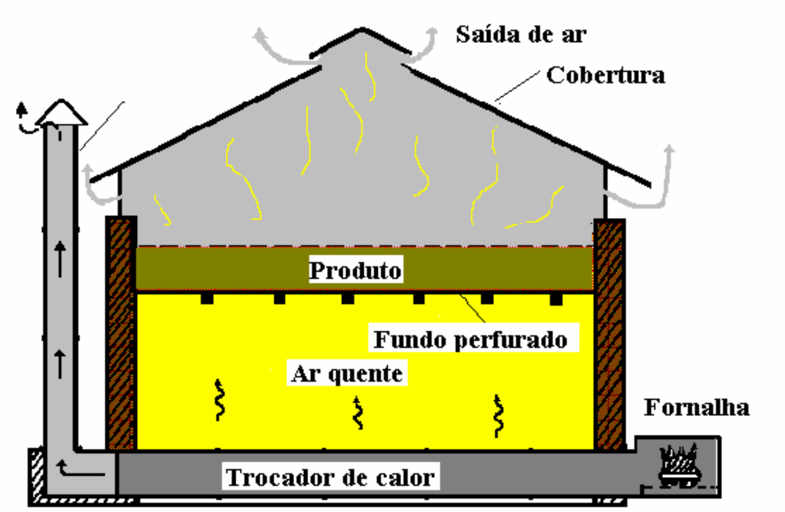



*Fig. 7: Longitudinal section of a natural convection dryer*

## 4. Concurrent Flow Drying of Coffee:

With the same objectives, as previously mentioned, in the laboratories of Universidade Federal de Viçosa an intermittent concurrent-flows dryer was designed, built and evaluated. Its architecture is similar to the counter-flow coffee dryer and has the following main characteristics: high thermal efficiency, a low initial cost, simple operation and maintenance.

With the evaluation model it was possible to dry natural coffee from an initial moisture content of 25% to 11% w.b. in 7, 6, and 5 h for drying air temperatures of 80, 100, and 120°C, with specific energy requirements of 5,700, 4,870, and 4,760 kJ $kg^{-1}$, respectively.

The dryer was built with an effective height of 4.0 m, capable of holding approximately 2,300 kg of natural coffee at 25% w.b. moisture content, and operating with an airflow rate of 27 $m^3$ $min^{-1}$ $m^{-2}$. The grain flows by gravity from a 1.5 m deep holding tank, enters a 0.7 m deep drying chamber, and then a tempering section 1.8 m high. The discharge auger located at the bottom of the dryer guarantees a coffee velocity of 3.5 m $h^{-1}$, so that the retention time of the coffee in the drying section is 0.2 h. The unloading device removes the partially dried coffee from the tempering zone and conveys it back to the holding section at the top of the dryer. It must be remembered that due to the evaporative cooling effect at the inlet of the drying chamber, the coffee does not reach the drying-air temperature.

Each drying test was compared with the traditional cement drying system. Even though using higher temperatures than those used for conventional high temperature coffee dryer, the quality deterioration in the coffee brew was not observed.

In order to verify the behaviour of the dryer operating under different drying conditions, drying simulations were made. These demonstrated that the maximum temperature reached by the grain increases with the drying air temperature, and for the same drying temperature, the higher the grain speed in the drying chamber, the lower the maximum grain temperature.

## 5. Combination Concurrent and Counter Current Dryer:

In a effort to reduce specific energy requirements and improve the efficiency during the drying of natural coffee, Pinto (1993 – *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*) proposed a new dryer design, as shown in (Fig. 8), which combines the counter flows and concurrent flows drying methods, in separate stages, in one single dryer. The inlet drying air is located halfway down the coffee column. Drying in the first stage is accomplished using the counter flows drying concept, after which the coffee flows directly to the second stage, where it will be dried as in a concurrent flows dryer. The dryer is fitted with a 60° gravity hopper which delivers the coffee to a central point below the tempering section, from whence it is transported to an elevator pit. The length of both the counter flows and concurrent flows drying sections is 1.1 m, and the dryer is capable of holding 4,500 kg of natural coffee at 30% w.b. moisture. Coffee velocity inside the dryer is 1.44 m $h^{-1}$, so that it takes approximately 0.8 h for the coffee to pass through each drying section in each drying pass.

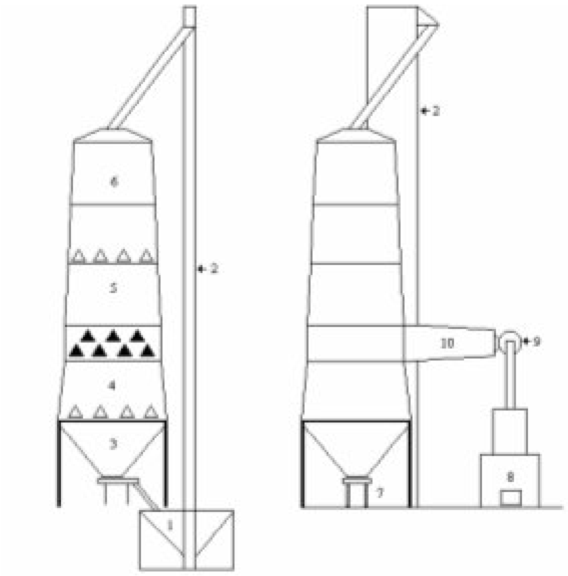


*Fig. 8: Details of a drier with mixed flows*

Table 2 shows the results of a performance evaluation conducted with experimental counter flows-concurrent flows dryer using drying-air temperatures of 80, 100 and 120°C, and an airflow rate of 20 $m^3$ $min^{-1}$ $m^{-2}$. The throughput (kg $h^{-1}$) is based on a 30% to 12% w.b. moisture reduction. A comparison of the results presented in Table 3 shows that total drying time and the specific energy requirement decreases by 44% and 6.4%, respectively, while the drying capacity increases by 80%, when the temperature is increased from 80 to 120°C.

*Table 2: Drying coffee in intermittent two-stage experimental counter flows-concurrent flows dryer*

| Drying-air temperature (°C) | Total drying time (h) | Specific energy requirement (kJ $kg^{-1}$) | Throughput (dry kg $h^{-1}$) |
|---|---|---|---|
| 80 | 22.5 | 6,070 | 200 |
| 100 | 15.7 | 5,660 | 290 |
| 120 | 12.6 | 5,680 | 360 |

Source: Pinto (1993 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality')*

Considering the small difference among the specific energy consumptions for the studied temperatures in drying tests with natural coffee (half dry), three drying tests with pulped coffee were conducted. The drying air temperature at 75°C was heated by an indirect heating furnace. The experimental results for Test 1 (initial moisture content 32% and 13% b.u. final moisture content) 10.3 $MJ.kg^{-1}$; for Test 2 (42% initial moisture content and 14% b.u. final moisture content) 5.8 $MJ.kg^{-1}$ and for Test 3 ((initial moisture content 24% and 14% b.u. final moisture content) 11.2 $MJ.kg^{-1}$. All of the samples presented the same drink quality (hard) and types 4/5, 5 and 4/5 for Tests 1, 2 and 3 respectively (Silva et al., 2001 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*).

## 6. Pneumatic Coffee Dryer:

The fixed bed dryer, a model widely used for pre-drying or coffee drying, does need stirring for product homogenization during the coffee drying process. When manually executed, the stirring operation uses great physical effort, mainly in the beginning of the coffee drying, when the product still has a high moisture content. During manual stirring, the fixed bed dryer entails: use of unnecessary labour, energy loss, and an increase in drying time.

For dryers with mechanical coffee stirring, increasing of the grain mass flow rate in the drying chamber give, in general, a product with better final quality. However, increasing the grain mass speed will increase the specific energy consumption because grains that pass by faster will lose less humidity per unit of time.

Besides these aspects, the systems for grain load/unload and stirring may cause difficulties in project installation, and increase maintenance and initial dryer cost.

A simple transport system, with a relatively low cost, is the pneumatic transporter. Used in storage facilities, this type of transporter has its origins in pressure equipment used to load and unload ships with grain. The pneumatic transporter moves grains by the use of high-speed air, through a hermetic piping system. With the pneumatic system the product can be transported in any direction, including along curved pathways. Another interesting aspect is its use in a fixed installation, which can be built without the need of significant structural changes.

*Fig. 9: On the left showing the furnace and cyclone;*
*on the right the two resting chambers (with the second mounted on the pyramids)*

Considering the advantage of the fixed bed dryer and the simplicity and low cost of the pneumatic transport system, a coffee drying system that allows the movement of the product (loading, unloading and stirring) and the flow of drying air, using a single centrifugal fan, powered by a 2 hp electric motor, was developed and evaluated. With these characteristics, the dryer can deliver up to 60 kg of dry parchment coffee per hour.

## 7. Dryeration:

The dryeration process involves both high temperature drying and aeration of the product is one of the most innovative drying methods that has been adapted to coffee drying systems.

In using the dryeration process, a high temperature drying process is concluded at about two per cent above the target moisture content and conveyed to a holding bin where it will be allowed to temper with no airflow for not less than 6 h. The coffee is then transferred to another bin where it will be cooled with low airflow rates. During the aeration or cooling some drying takes place and the remaining two percentage points of moisture are removed.

Dryeration provides three advantages over traditional coffee drying methods (Loewer et al, 1994; Cloud & Morey, 1980 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*):

- Increased dryer capacity;
- Reduced energy requirement; and
- Better coffee quality.

The effect of drying-air temperature and a tempering or steeping period on the moisture difference throughout a fixed bed of natural coffee, and energy requirement during the dryeration process, have already been determined (Cordeiro, 1982 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*).

Table 3 summarizes the mean values of final moisture content difference throughout a 0.4 m deep coffee bed for three levels of drying-air temperature (50, 60, and 70°C), one level of airflow rate (15 $m^3\ min^{-1}\ m^{-2}$) and three levels of tempering period (0, 6, and 12 h).

The values presented in Table 3 were obtained using natural coffee with 28% w.b. initial moisture content; the high temperature drying was interrupted when the moisture content of the coffee beans have reached 13% w.b., and two percentage points of moisture were removed during aeration or cooling.

Table 3: Values of final moisture content differences found between samples taken from the coffee bed (percentage point moisture, w.b.). Dryeration of a 0.4 m deep fixed-bed of *natural* coffee harvested at 28% w.b. and dried to 11% w.b. with an airflow rate of 15 $m^3 min^{-1} m^{-2}$.

| Temperature (°C) | Tempering period (h) | | |
|---|---|---|---|
| | 0 | 6 | 12 |
| 50 | 3.2 | 2.3 | 1.7 |
| 60 | 3.6 | 3.0 | 2.8 |
| 70 | 3.8 | 3.0 | 2.9 |

Source (Cordeiro, 1982 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*)

From the values presented in Table 3, it can be concluded that drying air temperature of 50°C and 12 h of tempering is the best dryeration treatment for natural coffee. It results in a final moisture difference of 1.7 percentage points; almost 50% less than the difference obtained with the conventional drying method.

It can be seen that that an airflow rate of 15 $m^3 min^{-1} m^{-2}$ significantly exceeds the values normally encountered in grain dryeration processes. However, coffee storage bins are generally not equipped with perforated floors. Thus the aim is to use the fixed-bed dryer as a tempering bin altogether, so that the fixed costs are reduced by using the same fan for both high temperature drying and aeration.

## 8. Combination High-temperature, & Ambient-air Drying:

Combination drying is one of the latest concepts in coffee drying technology. It is the drying method in which both high temperature processes and natural air or low temperature drying procedures are combined in an attempt to provide a high quality product as compared to using only high temperature drying.

The high temperature drying stage is used to reduce coffee moisture contents from approximately 60% w.b. to 25% w.b. (or less), so that natural air drying can be successfully used to complement the drying by further reducing the moisture content of the product to safe limits (Dalpasquale, 1984 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*).

Unlike the dryeration process, where coffee is allowed to temper in a separate bin for several hours before being transferred to another bin where it will be slowly cooled, in combination drying the hot coffee is transferred directly to the storage bin where the remaining moisture will be removed using ambient air or low temperatures.

In combination drying, coffee is dried in the high temperature dryer to a moisture level ten to twelve percentage points above the value for safe storage, with the result that the recommended minimum airflow rates for the aeration stage in combination drying are 15 to 25 times more than the maximum airflow rate used in the cooling stage of the dryeration process (Navarro & Calderon, 1982 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*).

Combination drying provides three advantages over typical high-temperature high-speed drying: increased drying capacity, reduced fuel requirement, and better coffee quality by reducing the final moisture difference throughout the coffee bed. As compared to the dryeration process, the main advantage of combination drying is the elimination of the extra handling step associated with the tempering bin. The main disadvantage of combination drying is the requirement of a relatively high level of capital investment and management in cases where it is purchased as a unit because two complete drying systems are included.

The usual procedure to dry *natural* coffee on the farm using the combination method is as follows: ripe cherries which have been strip-picked at moisture contents ranging from 50 to 65% w.b. are separated from the rest by water flotation and screening, and then dried in either two or three separate stages.

Where three stages are used, the coffee is firstly dried on paved sun drying terraces until it reaches approximately 35% w.b. Then, the partially dried fruits are conveyed to a high temperature dryer where their moisture content is further reduced to about 25% w.b. In the third stage the coffee is bin-dried to approximately 13% w.b. moisture using natural air.

In using two stages, the sun drying procedure is eliminated and the moisture content at harvest is reduced to approximately 25% w.b. using the high temperature dryer alone. Combination drying can also be applied to the drying of washed and pulped coffee, whereby the product is delivered directly to the low temperature drying bin after the sun drying procedure or the high temperature drying method.

A typical ambient-air drying bin used in combination drying for small-scale operations is 2.0 m in diameter and has an effective height of 2.0 m, a free volume of 6.3 $m^{3}$, and is capable of holding approximately 2,520 kg of coffee at 22% w.b. moisture content. The bin wall consists of one brick layer 0.12 m thick covered with plastering on both surfaces, and a reflectant paint is applied. The bin is equipped with a perforated floor for drying-air distribution and a 0.2 m square basal outlet is also provided. The surface of the coffee bed is generally open to the atmosphere but shielded from rain by a roof erected over the bin and supported on a wooden frame. The bins must be built over a concrete floor previously made damp proof. A straight bladed, centrifugal type fan driven by a 735W, 1730 rpm electric motor is used to force air upward through the coffee bed.

The natural air drying stage in combination drying has recommended airflow rates in the one to one to one-half of the airflow range normally used in the high temperature drying stage (Cloud & Morey, 1980 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*). Thus, airflow rates varying in the range from 7 to 15 $m^{3}\ min^{-1}\ m^{-2}$ are generally used. This is enough air to dry relatively wet coffee as a result of the drying capability of the natural air. The fan should be started as soon as the first lot of coffee is delivered to the bin, and is switched off during some periods of adverse drying weather, or when the mean moisture content of the coffee in the surface layer of the bed reaches the target moisture content. For natural air drying systems, the total drying time depends on the initial moisture content and prevailing climatic conditions.

The mixing of different lots of coffee of markedly different moisture contents, a common practice from the farm to the final product processor, should be avoided whenever possible. All tests carried out using mixed lots of coffee with different moisture contents resulted in brews of poor cupping quality. It is believed that only when all coffee has the same or similar moisture contents *prior* mixing, will it produce a brew with full flavour development.

It is expected that one or a number of bad weather days will not adversely affect the efficiency of low temperature drying systems. Stopping the fan and waiting for a more favourable weather would fail to recognize that the first and foremost requirement in ambient-air drying is to keep the grain cool and prevent heating (Navarro & Calerdon, 1982 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*).

However, it is a matter of common knowledge that keeping coffee at moisture contents over 15% w.b. for long periods of low-temperature drying or storage is unsafe since mould and, consequently, cup quality deterioration may occur. But rewetting of dried coffee as a result of continuous fan operation during periods of adverse weather is also a hazardous procedure because the beans may become pale and bleached out in appearance signifying aroma and flavour deterioration. Therefore, unlimited fan operation during poor drying weather conditions may be recommended as long as the moisture content of coffee is above approximately 17% w.b.

## 9. Physical Properties and Relationships of Interest:

*Notation*

$\Theta$ grain temperature, °C
$\varphi$ relative humidity, $0 \leq \varphi \leq 1.0$
$\rho$ bulk density, kg m$^{-3}$
$c_p$ specific heat of coffee, kJ kg$^{-1}$ °C$^{-1}$
$h_{fg}$ enthalpy of vaporization of water in coffee, kJ kg$^{-1}$
M moisture content of coffee, decimal dry basis
MR moisture ratio, $(M - M_e) / (M_0 - M_e)$
T air temperature, °C
$T_{abs}$ absolute air temperature, K
t time to dry to MR with drying air temperature Tabs , h

*Suffices*
e equilibrium value
eq equivalent
0 initial value

*Appendix - Physical properties*

**a. Thin layer drying equation.** The following equation describes the drying rate of a thin layer of natural coffee at drying air temperatures ranging from 40°C to 80°C (Arteaga, 1986 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*).

$$MR = \exp\left[-105.756\, t_{eq}^{\,0.60564}\, e^{(-2751.51 / T_{abs})}\right] \tag{1}$$

**b. Equilibrium moisture content.** One of the main problems in previous attempts in setting up mathematical models to simulate coffee drying was the lack of a reliable equation for its equilibrium moisture content. Rossi and Roa (1980 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*) presented the following empirical relationship for the desorption isotherms for natural coffee:

$$M_e = (15272\varphi - 32478\varphi^2 + 33341\varphi^3) \exp[(-0.029458 - 0.0016309\varphi - 0.013695\varphi^2 + 0.0132050\varphi^3)\, T_{abs}] \tag{2}$$

The resulting sigmoidal curve obtained from Eqn (2) is too steep for relative humidities above 60% and it does not fit well most of the experimental data found in literature. It is believed that many failures to validate coffee drying were due to the use of this equation to predict equilibrium moisture content. On the other hand, better overall accuracy is attained using the following empirical equilibrium moisture content equation proposed by Arteaga (1986 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*).

$$M_e = 1.1282 \; [-\ln(1 - \varphi_e) \, / \, (T_e + 40.535)]^{0.5405} \qquad (3)$$

**c. Enthalpy of vaporization.** The absence of an accurate equilibrium moisture content equation for coffee also led to inaccuracies in the development of equations for the enthalpy of vaporization of moisture in coffee beans. The following equation was developed by Berbert & Queiroz (1991 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*) and was based on the method of correlating vapour pressure and latent heat data presented by Othmer (1940 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*). It was developed using experimental data from Arteaga (1986 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*) in the 0.15 decimal d.b. to 0.25 decimal d.b. region.

$$h_{fg} = (2501 + 1.775 \, \Theta) \; [1 + 1.872 \exp(-20.601 \, M)] \qquad (4)$$

**d. Specific heat.** The following equation developed by Villa *et al.* (1978 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*) represents the specific heat of coffee at constant pressure.

$$c_p = 1.674 + 2.510 \, [M \, / \, (1 + M)] \qquad (5)$$

**e. Bulk density.** The effect of moisture content on bulk density of natural coffee is given by the following equation developed by Silva (1991 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*).

$$\rho = (396.48 + 224 \, M) \, / \, (1 + M) \qquad (6)$$

In a study conducted by Castro (1991 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*), the estimated bulk density of washed coffee as a function of moisture content was defined as in the following equation

$$\rho = 371.78 + 255.17 \, M \qquad (7)$$

f. **Volume reduction.** The grain volume shrinkage is generally assumed to be negligible during simulation studies of the drying processes. This is based on the assumption that the decrease in bed height is not substantial for most cereal grains in continuous-flow dryers (Brooker *et al., 1974* - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*). However, the assumption of negligible volume shrinkage for natural coffee during drying can impose serious limitations in simulation accuracy. Kinch (1967 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*) reported a pronounced reduction in the volume of parchment coffee during drying. Volume reduction of 23.5% was observed when drying from 55% w.b. to a final moisture content of 12% w.b. No correction for bed height variation due to volume reduction are applied to the coffee simulation models because to date no really comprehensive study describing the phenomenon for natural coffee has been undertaken.

g. **Pressure drop.** Guimarães (1995 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*) observed that the pressure drop in experimental drying tests run with natural coffee was always smaller than 7.5 mm of water column per meter depth of coffee, whereas for pulped coffee this value was 10.0 mm H2O per meter depth. Direct comparison of these results with published data is rather difficult because of differences in particle size, bed depth, porosity of the bed, and surface roughness. Besides, the amount of reported data on the pressure drop through beds of coffee is meagre. However, it is realized that a pressure drop of 7.5 mm of water column per meter depth of clean coffee is smaller than those values normally found in practice where foreign material will occupy some of the free space between the cherries, hence apparently compacting the bed and increasing the pressure drop. Afonso (1994 - *see: Selected bibliography under Section 3, specifically the section on 'Coffee Processing and Quality'*) made a series of measurements of pressure drop through beds of coffee. For a bed depth of 1.75 m and airflow rates of 10.2 and 9.9 m3 min-1 m-2, the pressure drops were 5.1 and 5.4 mm of water column per meter depth, for 23% and 14% w.b. moisture coffee, respectively.