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KILN DRYING OF SAWN LUMBER *

by

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1. Reasons for drying wood

Modern wood drying techniques received their main stimulus from the acquisition of fresh knowledge on the physical nature of wood and the processes involved in its drying.

Conifer woods in general have a relatively dry heartwood duramen (31 to 35 per cent moisture content) and a sap-wood with high moisture content of 120 to 160 per cent. Exceptions are the strobile pine with heartwood moisture content around 80 per cent and the "wet heartwood" of white spruce with moisture content up to 220 per cent. With latifolius woods the moisture content differences between sap-wood and heartwood are less marked. In general, moisture content increases towards the top of a tree where sap-wood predominates. Moisture content decreases with age therefore wood has more moisture in young forests than from mature ones. In general more moisture comes from uneven aged forests than from even aged forests.

Some of the moisture in wood is in a free state in the cellular and intercellular cavities (free moisture). The rest is found in the cellular walls (hygroscopic moisture). Hygroscopic moisture represents from 30 to 38 per cent of the weight of the dry ligneous material (saturation point of the cellular walls).

In an unsaturated environment (unsaturated air) the free moisture (that exceeding the saturation point of the walls) is subject to evaporation.

As regards the moisture on the cellular walls, the wood may be considered as a hygroscopic body which allows an exchange of moisture with the environment (air). Within the moisture range somewhere between 0 and saturation point of the walls the wood assumes a moisture content which is in equilibrium with the relative humidity and temperature of the surrounding air (Table 1).

The two processes are not entirely reversible and it has been ascertained that, for equal pressure differences, a lower moisture content of the wood is obtained by absorption than by drying. This phenomenon called hysteresis results in a difference between the two processes of 2 to 4 per cent in the wood's moisture content (Giordano, Tecnologia 1, Fig. IV. 32 and 33) and is explained by the theory that a part of the hydroxides is balanced and "with a reduction of the wettability of the dry surfaces".

Together with this phenomenon is also noted a much lower rate of moisture absorption compared with the rate of drying. Wood therefore possesses a certain hygrosciopic inertia, more marked when increasing than decreasing.

When hygroscopic moisture decreases, the wood shrinks and when it increases the wood swells.

The anisotropy of shrinkage i.e. the ratio between the three linear shrinkages in the majority of woods is approximately:

$$a_1 : a_r : a_t = 1 : 10 : 20$$

The expression for the co-efficient of shrinkage $K = \frac{a}{30}$ is frequently used in technological calculations.

Table No. 2 gives the average shrinkages referring to dimensions of wood in the green state. Shrinkages are also a specific feature of wood but can also vary within the same species at quite wide intervals. Table No. 1 also gives the ratio between tangential and radial shrinkage which is useful as a value for the deformability of wood. This effectively increases with an increase in the ratio $\frac{at}{ar}$.

Shrinkage virtually begins when the wood's average moisture content is in excess of 30 per cent because the external layers begin to lose saturation moisture even though the internal layers are still very humid.

The average moisture at which shrinkage will begin depends in practice on permeability, thickness, initial moisture, intensity of drying and mechanical strength (plasticity, tensile and compression strength).

The influence of the non-homogeneity of wood is:

- shrinkage increases with density $B_v = 0.27\ d_b$ (Stamm);
- the spring wood shrinks less than the late season wood;
- the heart-wood shrinks less than the sap-wood.

Non-homogeneity together with anisotropy is the source of deformation and increased starshake.

Finished wood products will tend to adapt to their environment and therefore they must be provided with moisture in equilibrium with local climatic conditions. As an approximate guide to conditions in Italy see Table 2.

Environmental conditions normally vary according to season and room air conditioning. If the variations remain within the hysteresis limits the moisture content of the wood will not vary, providing the moisture content has previously been brought down to the lower limit.

Due to hygroscopic inertia the moisture content of the wood will not vary even in the event of occasional changes outside the above-mentioned limits. The hygroscopic inertia increases with density and thickness of the wood, as well as with the quality of varnishing and water-repellent characteristics of the products used to treat the wood.

Any variation of the saturation point also causes dimensional variations and deformation (Table 1).

The permeability of wood is the most important factor in the drying process. Permeability in the radial sense is noticeably greater than in the tangential sense; the reason why laterally sawn boards dry much quicker than radial ones. Permeability in the radial sense increases with the number of radii.

The number and frequency of radii are unfortunately the cause of lowering the transverse tensile strength of wood which leads to starshake.

Red spruce and all sap-woods may be considered as permeable while white spruce and the heart-woods of other conifers may be considered of medium permeability. Among latifolius woods the most permeable are those with diffused prorsity while tylosed woods are definitely impermeable. Lightweight white woods are permeable. Permeability in general is correlated to density.

2. Technology and general rules

If not immersed in water soon after sawing, wood immediately begins to dry by evaporation of the superficial free moisture (phase 1). With the continuation of this process in depth, by the diffusion of the vapour created in depth through porosity and in part by capillary action in permeable woods, there will already be a fairly uniform parabolic moisture gradient in the thickness before the 1st critical point. With medium permeability woods vapour diffusion and capillary action will be less and the diffusion of moisture through the cellular walls will soon predominate. In this way the moisture gradient in the thickness will be steeper and will become parabolic as soon as the external layers are in equilibrium with the surrounding air. Mechanical strength at this phase is minimal. High temperatures are dangerous.

The reaching of the saturation point of the cellular walls in the external layers marks the beginning of shrinkage and the appearance of tensile stresses; [more marked in the external layers of medium permeability woods (1st critical point)] and the beginning of the slowing down of drying (phase II). The wood's average moisture content at the 1st critical point will be around 2/3 of the initial moisture content plus 10 per cent in permeable woods and around 2/3 to 3/4 of the initial moisture content in medium permeability woods.

On reaching an average moisture content of 21/24 per cent drying enters into phase III where we have: a) inversion of stresses (centre stress) and b) external layers in all cases in equilibrium with the final climate which is normally very dry (2 to 5 per cent). Mechanical strength of the wood increases in this phase. Drying slows down because with the movement of moisture its diffusion throug the cellular walls predominates.

Drying is faster when permeability is higher, when density is lower, when temperature is higher, when relative air humidity is lower, when the air circulation is faster; the latter losing its efficacy in phase III.

3. Drying media

3.1 Air and furnace gas

The main characteristics of air: temperature, pressure, volume, weight, humidity and heat content are interdependent according to the well known fundamental laws:

GAY-LUSSAC: Volumetric thermal expansion is identical for all gases and is 1/273 of the initial volume for each ^{o}C;

BOYLE-MARIOTTE: an increase in pressure corresponds to a decrease in volume (at constant temperature);

DALTON: the pressure of a gas mixture is equal to the sum of the partial pressures of its individual components.

From these three laws it follows that:

- the weight of air is proportionate to its pressure;
- water vapour diffuses in air towards the lowest pressure zones;
- for a given atmospheric pressure of the air-vapour mixture a temperature rise will correspond to an expansion of the dry air and a decrease in its pressure so that an increase in vapour pressure will result. It can be stated therefore that a rise in temperature allows the air to absorb larger quantities of vapour.

The maximum vapour pressure possible in humid air is called "saturation pressure".

If the effective pressure of the vapour P_v, for a given temperature, is less than that of saturation P_{vs}, the air is not saturated. The ratio between these two values is called "relative humidity of air".

The humidity of air can also be expressed as a ratio between the water vapour content of the air and the weight of the water vapour in the saturated state.

The weight of the water vapour content in 1 kg of dry air is called "absolute humidity of air".

The relative humidity of air is generally expressed as a percentage, i.e. multiplying the ratio φ by 100.

A relative humidity of the air lower than 100 per cent signifies that the vapour pressure of the air is lower than the saturation pressure; consequently the air can absorb water vapour from zones where the pressure of the latter is higher (evaporation).

The maximum quantity of moisture the air is able to absorb depends on the temperature.

The maximum quantities of moisture (saturation humidity) for various temperatures are indicated in Table 3, valid for normal total atmospheric pressure of 760 mm mercury column (1 atmos. = 1.033 k_p/cm2).

The heat of humid air is equal to the sum of the heat content of the dry air and the vapour. To calculate this air heat at a temperature of t °C the specific heat of the air and the transformation heat from the 0^o condition to the condition under examination must be known.

Specific heat is the quantity of heat (in calories) required to raise the temperature of a 1 kg body (mass) through 1^oC.

The definitions of heat involved in the subject under discussion are as follows:

- specific heat of dry air: 0.24 Cal/kg;
- specific heat of water: 1.00 Cal/kg;
- specific heat of water vapour: 0.46 Cal/kg;
- evaporation heat of water at 0^oC: 595 Cal/kg.

The calorific content of air depends on its absolute humidity and its temperature t. The heat of dry air is given by $i = 0.24\ t$ Cal/kg. As regards humidity, which appears in the form of vapour, its heat amounts to 0. 46 t x Cal/kg. Furthermore the heat required for evaporation is also present in the vapour i.e. for transforming the water into vapour and corresponding to 595 x Cal/kg.

The heat content of 1 kg of dry air containing x g of water vapour is calculated with the formula:

$$i = 0.24\ t + x(595 + 0.46t)$$

In this way we arrive at the rule in which the heat content of air for a given temperature increases with increasing humidity.

In drying, the air can carry out the double function of heating the material (wood and moisture) and evaporating the moisture or simply evaporating moisture. In both cases there are changes in temperature and humidity which is reversible with conditioning. The conditioning of air is intended in the restricted sense of the following processes:

- temperature increase by heating i.e. by adding heat;
- temperature decrease by cooling i.e. by reducing heat;
- relative humidity increase by moistening i.e. by adding vapour;
- humidity decrease by moistening i.e. by adding vapour;

- humidity decrease by drying i.e. by removing vapour by partially changing the air or by partial condensation of the vapour in the air.

These processes may be easily followed on the graph " i-x " (Fig.1).

During a drying phase the re-circulating air enters the pile of wood with the characteristics given under point 1 and leaves it with the characteristics of point 2 on graph " i-x " (Fig.1). How is the re-circulating air brought back to the characteristics of Point 1 ?

a) Partial exchange of the air: let us assume that the external air has t_o = 25°C and φ = 60 % represented on graph " i-x" by point 0.

The air circulating through the pile absorbs a quantity of water vapour equal to Δx = 141-129 = 12 g/kg. Its temperature is reduced to t_2 = 70°C. The straight line connecting points 0 and 2 represents the change in the characteristics of the mixture. Sufficient external air is allowed to enter for the mixture to reach the characteristics of point 3 so that the x of the mixture equals that of point 1 i.e. x_1 = 129 g/kg.

A tenth part of this air is substituted for external air so as to return to absolute humidity x_1 = 129 g/kg.

With this operation the air temperature is further reduced to t_3 = 66°C and the heat content from 105 to 95 Cal/kg (point 3 on the graph). To return to the conditions of point 1 the mixture must be heated by adding 10 Cal/kg. The operation is represented on the graph " i - x " by the griangle 1-2-3 which is appropriately called "drying triangle".

b) Partial condensation of the vapour of the humid air: the air leaving the pile must be cooled to below dew-point.

From point 2 the process follows the vertical x = 141 = const. until it reaches the curve φ = 10 %. Continuing with the cooling the process follows the curve φ = 100 % thus decreasing the absolute humidity until x_1 = 129 g/kg is reached (point F with a temperature of 57°C). At this point the air is heated to 95°C. The process now follows the ordinate x = 129 g/kg - const. and stops at point 1. Thermal balance in this case is:

for condensation	105-92	=	13 Cal/kg (refrigeration units)
for heating	105-92	=	13 Cal/kg
total heat loss			26 Cal/kg

From this example it is clear that, for drying techniques, thermal balance is more advantageous with the system of partial air (case a) than with that of partial condensation (case b).

Furnace gases have characteristics similar to air and can be mixed with air and vapour for conditioning purposes.

3.2 Steam

The hygroscopic equilibrium of wood in saturated steam at normal atmospheric pressure is a few percentage units below the saturation point of the cellular walls.

Superheated steam has a temperature higher than that of saturation for a given pressure. Saturated steam (e.g. at 115°C) should have, according to the steam table, a pressure of 1.7239 kp/cm2. Superheated steam is not saturated (in our example its relative humidity is $\frac{1.0332}{1.7239} = 0.6$) and therefore it tends to cause evaporation i.e. to absorb steam and to heat. Precisely stated it liberates thermal energy and cools down even before condensing. Due to these qualities it can be used for the artificial drying of wood.

3.3 Vacuum

A vacuum has the characteristic of lowering the boiling point of water as follows:

Abolute pressure p_o mm Hg	Boiling point t_{bp} °C
760	100
355	80
150	60
55	40
18	20

Due to this fact the vacuum has for a long time been successfully applied in medicine, biology and in the food industry for dehydrating perishables. Ways are also being sought of applying the vacuum for drying wood which is very sensitive to high temperatures.

Besides the method of water evaporation, vacuum drying can also be affected by the sublimation of ice for which, due to working temperatures of $-30^{\circ}C$, a very high vacuum is required (p_0 = 0.2 ... 2 mm Hg).

3.4 High frequency electric energy

Having high dielectric properties (Vol. I + IV.6.2) wood lends itself to the use of high frequency energy as a heat source for hygrothermal treatment. Frequencies from 2 to 4 MHz are used.

Tests have even begun recently on internal heating with microwaves at frequencies above 900 MHz.

3.5 Infra-red rays

Wood is a good absorber of infra-red rays (1 ... 2 u) but its permeability to them is low, depth of penetration being only 4-5 mm. It hardly reflects them and therefore heating is without loss of energy. Due to limited penetration this form of heating has an effect similar to that of convection or contact heating.

3.6 Liquids

Of the hydrophobic liquids (those which do not mix with water) those having higher boiling points than water are used: linseed oil, coaltar oil, but above all solid residues from petroleum distillation, commonly known in Italy as paraffins, and composed of paraffin, ceresin and high viscosity oils (a yellow mass fluidifying at $50^{\circ}C$ and boiling at $250^{\circ}C$). These materials are non-toxic and their weight per unit volum 0.9. Treatment is by immersion.

Heating and drying conditions are similar to those of superheated steam treatment.

Azeotropic mixtures are those having a lower boiling point than their single components. Mixtures containing water for example boil below $100^{\circ}C$ (a water-tetrachloroethylene mixture boils at $87^{\circ}C$). This characteristic is very useful for eliminating part of the moisture from wood because the vapours from the mixture condense and can be separated.

Polar hydrophile organic solvents, soluble in water, are very useful for also eliminating the wood's extracts along with the moisture. For this purpose acetone, alcohols and ethers may be used. After extraction the solvents are re-distilled.

3.7 Organic solvent vapours

Solvents insoluble in water are used such as xylol, toluene, tetrachloroethylene or fractions of tar distillates with low boiling points. The evaporation heat of these solvents is lower than that of water and transmission co-efficients of heat very high.

Organic solvent vapours are applied for vacuum drying of wood.

3.8 Saline solutions

The vapour pressure of a saturated saline solution is lower than that of water vapour. For this reason moisture flows from the wood to the solution.

Salts or hygroscopic compounds such as common salt, urea, molasses or invert sugar, polyethyleneglycol, are used in solutions of two or even three components for other purposes besides that of drying the wood; in particular that of reducing the hygroscopicity of the wood and increasing its dimensional stability.

4. Air seasoning (drying)

The principal aim of seasoning is to reach a level of moisture content which guarantees security from attack by micro-organisms and insects (18 - 20 %).

The minimum humidity attainable by seasoning depends upon micro-climatic and other local conditions which can vary in Italy between 8 and 20 %. It depends mainly on season. The humidity of wood, already seasoned and left in the open, varies during the year according to climatic variations.

For seasoning, planks are normally placed on open sites, chosen according to requirements for drying, which are fenced in and divided up into lots with space for transport between them. The ground must be tamped flat, dry and free of organic material.

The size and number of piles depend on the transport system used and climatic conditions. The more ventilated and dryer the site, the wider the piles can be (1.2 - 4 m); the distance between piles should be 0.75 to 2 m. The positioning of the planks with respect to direction of prevailing winds is studied case by case.

Immediately after being sawn, planks for seasoning must be brushed and spaced with laths and auxiliary material treated with antiseptics. Piles must always be covered and, in the case of valuable woods, their ends must be protected.

Bases for piles consist of concrete pillaring with wooden or reinforced concrete cross pieces so that the bottom planks are at least 30 cm above ground level.

Covering for the piles should be sloped so as not to impede air circulation and also to protect the planks from rain and sun. Piles too exposed to the sun should have their flanks protected with wood, cane, etc. The higher the humidity the greater the distance should be between planks in the horizontal rows (if necessary with a vertical vent in the middle of the pile).

Piles can reach a height of 7 m. Normal heights are 4.5 to 5 m.

Each pile must be composed of uniform material as regards type of wood, tyickness and initial humidity.

Other grades are piled according to specific needs, such as: in crib piles or box piles, up to 7 m long and up to 1.5 m wide; sometimes on edge to help drying. Very short semi-finished stock is separated according to width and thickness and spaced with stickers if longer than 70 cm.

Sawn lumber first grade is air-seasoned in sheds) or under fixed roofing) provided with adjustable openings for efficient air circulation. Fixed shelving is used for scaleboard.

Methods to facilitate seasoning: boards placed upright (pre-seasoning of freshly sawn lumber and those susceptible to stain, such as birch, maple, poplar): centrifugation possibly combined with gravitational action, forced air circulation, solar kilns. Due to their doubtful economic validity these methods are only applied in special cases.

Storage capacity for seasoning is subjected to much variation depending on numerous stacking factors. An average figure, for standard piling is height of 5 m (0.5 to 1m/m2).

5. Kiln drying

Kiln drying has become vitally important to the timber trade and to allied wood working industries and technology should be fully applied when shortening drying time making more economical the entire operation, also on reducing the damage possible to wood by using inferior methods.

Kiln drying differs from air seasoning in that the desired result may be achieved by using media where conditions can be artificially modified to determine the required variation of the moisture content. The principal modification is increasing the temperature of the medium acting as an important stimulator on the movement of moisture in the wood, making it possible furthermore to bring the material to any desired final humidity.

We shall be dealing ere with drying processes which, at the present time, are more widely used industrially and also economically justifiable.

5.1 Drying with partial air exchange

5.1.1 Process

The air circulates between horisontal layers of spaced planks and is re-circulated through the drying chamber by fans.

Besides being the drying medium the air, in this case, is also the heating medium of the wood which contains a certain moisture content therein (convection heating). The effect is for the air to humidify and cool and it is necessary to recondition it by heating and partial exchange with external air (Fig.1).

The process of kiln drying wood consists of:

- preliminary treatment (pre-heating);
- the actual drying
- various treatments for improving the condition of the material (quality of drying) supplementary treatments.

Initial material requirements for efficient drying are: uniformity of type of wood (density), uniformity in manufacture; all material be from the same part of the log; absence of case hardening, internal stresses, and uniformity of temperature in thickness.

Pre-heating is simply carried out with relative humidity of the air at least 90 % if green wood is involved. If the wood is pre-seasoned in hygroscopic equilibrium with it the temperature is increased by 10 - 15°C. Duration in hours equals the number of mm thickness. Half the time is used for gradual increase in temperature; the other half for constant final temperature.

Factors for the choice of drying conditions are: thickness and density of wood, content of extractives and various substances (fats, oils), rate of air circulation. The greater these factors are, the lower the temperature and higher the relative humidity of the air should be.

According to modern wood technology, drying should be carried out as follows:

- with a constant degree of drying at least during the first two phases (the degree of drying is the ratio of moisture of superficial layers and the moisture of equilibrium of the wood versus the climate of the drying air);

- with a low temperature, constant in the first two phases and increasing in the third phase;
- with relative humidity of air, constant in phase I and diminishing in successive phases.

The relative humidity in drying kilns is usually measured with a psychrometer which indicates air temperature (dry temperature) and evaporation temperature (wet temperature). The rule for the humidity condition is therefore expressed as follows:

Drying is carried out with humid temperature constant in phase I, diminishing in phase II and constant in phase III. The drying condition with a psychrometer is expressed graphically in Fig. 2 a.

The conditions recommended by us for drying various types of wood and for thicknesses up to 30 mm are given in Table 4. For greater thicknesses the temperatures are lowered and the degree of drying diminished as necessary. Instead of fixing the two temperatures, their difference (psychrometric difference) may be fixed as in the table. The psychrometric difference is kept constant in phase I, increased slightly in phase II with a larger increase in phase III.

The progress of drying must be checked by weighing the test planks, conveniently placed in the pile, to which we shall assign the same initial humidity found in the test specimens for determining the wood's humidity.

For large kilns, automatic control of drying is more convenient based on continuous measurement of humidity in test planks by electrical means.

Fig.2 b shows graphically the drying condition which proceeds by automatic electronic control with hygrostats. The process has been planned cautiously because it puts back the first climatic change to critical point II which lengthens the drying cycle. Such cautiousness is not necessary for conifers.

In the case of spruce, pine and tropical white woods, where a high quality of drying is not called for, the progress of drying can even be controlled by timers.

It is very difficult to forecast a rational duration of drying due to the complexity of factors influencing its progress.

The presumed times, calculated by whatever method, can only be considered as rough estimates. Calculation can serve to evaluate the times at which the critical points are reached as well as times to bring drying to an end even if contact with effective progress has been lost.

We have developed a method of calculating drying time based on the following proportionalities:

- Fickian permeability $K \ln \frac{u_i}{u_f}$; K = co-efficient of permeability
- Wood thickness S^n; n = 1.25 - 1.5
- Specific gravity of wood p_o^n ; n = 1.5
- Degree of drying $\ln \frac{u_i}{u_e}$

For other factors linear proportionalities are applied.

To avoid uncertainties in determining K the calculation assumes an ideal drying cycle which, for the conditions of the case under examination, is weighted with the above mentioned proportionalities.
Ideal time O_m = 22 hours, u_i = 60 %, u_f = 10 %, s = 25 mm, P_o = 0.4 red spruce, u_i/u_e = 3), temperature 75 - 90°C.

The following factors are also taken into account in the calculation:

- width of planks	for this data refer to Table VII.18 in the volume mentioned in the foreword	
- efficiency of drying		
- orientation of planks		
- length of planks	1.2 - 1.5 m	1.6 - 2 m
- width of piles	1.2 - 1.5	1.6 - 2 m
factor	1	1.2 - 1.5

For supplementary treatment in the drying of conifer and soft latifolius planks it is generally the rule to apply only the equalization of humidity which, at the end of the drying process, varies between different planks. Procedure is with conditioned air acting on the wood's average humidity; the temperature being raised simultaneously. Latifolius hardwoods are given a final "conditioning" treatment consisting of equalizing the internal humidity of the planks (lowering of humidity gradient). This is necessary in the case of moisture pockets in conifer woods (white spruce, hemlock) when operating with very humid and hot air (humidity climate 3 - 4 % above the average of the wood at the beginning of conditioning). The operation is more successful if carried out near the middle of phase III than at the end. The same operation will serve for sterilization and elimination of mildew appearing during drying, as well as for "reconditioning" the wood in the case of too steep a humidity gradient inside the planks (case hardening).

Artificially dried wood should be stored so that it is protected from seasonal climatic changes. This is advisable even if it is to be used soon after treatment, especially in the case of bulky hardwood assortments which have to undergo further cutting, because elimination of stresses in the kiln is difficult and costly. With the passing of time the stresses due to plastic ceformation will be relieved. With humidity not too low and the planks piled without spacing laths (12 - 14 %) storage can be in a closed building having adjustable ventilation. If, however, humidity is low (6 - 8 %) and planks remain spaced with laths as they come from the kiln, the store must have air conditioning. In the case of piles without spacing laths there will be a better stress relieving effect.

5.1.2 Engineering

Drying kilns are chambers or tunnels made from masonry or sheet metal. The are <u>waterproof</u>, <u>corrosion resistant</u> (vapours and acids) and <u>insulated</u> to prevent imbalance in the conditioned air.

Present day kilns have equipment for air ciroulation and conditioning mounted internally.

Drying of conifer planks is relatively fast, involving considerable evaporation per unit of time, thus calling for much heat and high air circulation rates through the pile (3-5 m/s).

In Central Europe, for conifer planks, the preference is also for chamber type kilns (periodic action). A few examples are shown schematically in Figs.3 and 4. All types of construction are valid providing air circulation is fast and uniform. The drying process is shown schematically in Fig.5.

When large quantities of wood are handled by fork lift trucks, the rational method is the building of large chambers with direct loading from the trucks, especially when large and dense planks are involved (Fig. 4d). The capacity of these chambers can reach 500 m3.

In modern tunnel type kilns the problem of conveyance, continuous, or intermittent for separate piles, is solved by a series of chain driven trucks or by motor driven roller conveyor. The three main tunnel drying systems are shown schematically in Figs. 6 a,b,c.

Laths should be treated, dried and trimmed and the thickness x length ratio should be at least 1 x 1.5. The thickness of the laths should normally be 1/2 or, at the most, 2/3 the thickness of the planks. They should be handled with care and kept under cover.

Circulation of air through the piles is taken care of by fans which can be axial or radial providing they have high capacities with low consumption of electric energy. Air heating is generally provided by hot water or steam radiators, fuel for the boilers being either liquid or waste wood. Costs for the various sources of heat must be taken into consideration. Electric energy as a heat source is, for example, very expensive in Italy. In some Scandinavian tunnel kilns the heat from the discharged air is partially fed to the heat exchanger for pre-heating the incoming air (Fig. 6 d).

In the majority of cases, de-hydration of the air is carried out by partial exchange of air from the chamber with external air through ducts with adjustable shutters.

There also exist plants with partial condensation of the air moisture in a circuit with cooling below the dew point with subsequent heating at drying temperature through internal cold water exchangers.

The air is humidified by simply spraying with saturated vapour in air circulating inside the chamber.

Besides the automation of the drying cycle by electrical measurement of the humidity of the wood in the chamber, there are various empirical automatic systems based on time and on the relative humidity of the air which, for conifer and latifolius soft woods, can operate reasonably well providing they include initial and final checking of the wood's humidity by the weighing method. Of these two checks the final one is the more important for any required intervention with treatment according to the state of the material. These systems are definitely not advised for drying latifolius hardwoods.

5.2 <u>High temperature or steam drying</u>

Where very rapid, rather than quality drying, is called for, permeable conifer woods and latifolius softwoods are suitable for drying at temperatures above boiling point. Non-saturated steam (superheated) is more suitable than air for this purpose because the drying condition is milder.

The surface of the boards darken but internally they remain white. Fissures can be avoided because the wood's plasticity at these temperatures is maximized. In applying this process the wood swells more slowly and therefore is considered more stable.

The kilns are made exclusively of metal and tightly sealed because climatic regulation is very critical and, with steam drying, infiltration of air must be avoided. The chambers are relatively small (on an average for 5 m3 of wood).

Drying times are from 1/4 to 1/3 those for conditioned air. In spite of this positive fact the system has not been widely used industrially.

5.3 Drying by partial condensation of air-borne moisture with refrigerator (heat pump).

Theoretically this drying process is that already described in 5.1.1. The essential difference resides in the fact that the reduction of the absolute humidity of the air in the drying chamber is done not by partial exchange of the air in the chamber with external air but by extraction of a part of the water from the air, causing condensation with its cooling below the dew point in the refrigerator, keeping step with the changes in the air as per Fig. 1. The same air is always circulating in the chamber without being exchanged. Although the process is not new it has only recently been widely adopted industrially with an Italian patent assisting the launching.

The specific features of this process derive from the fact that, until now, electric energy has been the only source of power. Economy has therefore been necessary, especially in Italy where electric energy is costly, so that temperatures and humidities have been kept at fairly low levels. Processing times then become longer especially in drying phase III where temperature is the only factor in the drying rate. To this fact is added the problem of the large quantities of vapour produced in phase I for drying softwoods so that there are large humidity gradients in the air in the pile. All this has led to overdimensioning the plants.

The fact of low humidities of the air also determines the humidity gradients inside the wood, especially in those plants having very low air velocities and not provided with air humidifiers.

The process is clearly illustrated in Fig.7. In order to economize on electric energy, and partially regulate the relative humidity of the air according to the requirements of the various woods involved, certain processes provide for differential cyclic functions with temporary stopping of the compressor to alternate condensation phases with those without condensation.

A plant for the condensation process consists of a drying chamber having the characteristics already mentioned. Where electric energy is costly the insulation must be carefully considered because drying times are long and thermal losses can be greater than effective power oonsumption.

The refrigerator, which may be fitted either inside or outisde the chamber, is built as shown in Fig. 7a. The condenser can be used for the first heating stage (heat pump) of the air after its cooling in the area of the evaporator. Definitive heating is by a supplementary electric radiator.

In those plants where only part of the air passes through the refrigerator, extra recirculator fans are fitted. Part of the air can also recirculate internally under the influence of the air stream entering the chamber at high speed from the refrigerator, through inlets on the ducting.

The pre-heating phase uses the electric radiator but steam or hot water can be used to save electric energy.

Other features of condensation drying are: absence of fumes (very important when drying offensive smelling woods in inhabited areas) and the fact that assembly is reduced to a minimum, when compared with air exchange driers (very important for small industrial and artisan type plants).

5.4 Vacuum drying

The lowering of the boiling point temperature with decreasing atmospheric pressure signifies a noticeable increase in the rate of evaporation at relatively low temperatures. This is very important for drying wood because lower temperatures also decrease the danger of damage, particularly during the first two drying phases. It has furthermore been discovered that with decreasing pressure the permeability of the cellular walls increases rapidly. For these reasons the possibility of applying vacuum technology to wood drying was for a long time under examination. A much wider industrial application of the vacuum for wood drying has recently been introduced in Italy with a "discontinuous vacuum" cyclic process. Attempts to use "continuous vacuum", in spite of qualitative results, have so far not found acceptable economic solutions.

Besides initial pre-heating, the drying process consists of a series of cycles: a heating phase followed by a vacuum phase. The wood is gradually brought up to the required temperature, keeping its internal temperature gradient as low as possible. As a rule the temperature will be somewhat higher than boiling point corresponding to the vacuum applied. A subsequent increase in the vacuum causes immediate evaporation of surface moisture and lowering of the surface temperature to the boiling point and below. With this there is the first reaction of a decreasing temperature gradient from the centre to external layers and consequently moisture tends to migrate from centre to surface to which is also transferred the heat which maintains the boiling point temperatur, thereby permitting continuity of moisture evaporation from the wood's surface. In penetrating the wood the rate of diffusion of the vacuum is increased within the surface; boiling follows and there is consequent internal evaporation, as well as diffusion of vapour, through the wood's capillarity, providing permeable and non tylosed wood is involved. The effect is also to cool the wood internally down to the dew point and subsequent stopping of the process, after which a new heating phase is introduced. It is presumed that the above phenomena combine to cuase continuous moistening of the wood's surface, as a result of which an essential reduction of the humidity gradient inside the wood is noted. In many cases there is an absence of this reduction or even a small decreasing gradient towards the centre at the end of the drying cycle.

Vacua reach a maximum of 740 mm Hg below normal atmospheric pressure (25 mm Hg absolute pressure). Temperatures and heating rates roughly follow normal rules. The higher the permeability of the wood and the higher its transverse tensile strength, the higher the temperature can be. During heating phases temperatures can be controlled by inserting tele-thermomoters in the wood. Furthermore, as drying progresses, temperatures increase by 20°C or more according to the type of wood involved. Durations of vacua, as a rule, are controlled according to thickness and density of the wood. Drying times are very much shorter than those with conditioned air drying. The higher the permeability the shorter the time which can reach upt to 1/5.

There are two processes in particular which differ from each other in the heating phase. In one case the heating is by means of plates, in the other case by means of conditioned air (in equilibrium with the moisture content of the wood) re-circulating between the planks by means of fans.

A heating plate type drier is shown schematically in Fig. 8 a.

A drier with circulating air heating, having heat and oil regeneration, is shown schematically in Fig. 8 b. These driers, because of their need to regenerate energy, are built with two autoclaves in tandem. Heating of the re-circulating air takes place on the internal surface of the autoclave which is heated by hot water or steam circulating around it in the space created by an external insulated envelope. The regeneration of heat concerns the air and steam, which are pumped by the autoclave, as well as the pump oil which is heated by the energy losses in the pump. For each of these sources of energy a separate heat exchanger is provided. This solution is adopted ifheating is by means of hot water.

The two autoclaves function by alternating the two phases of the cycle.

While one autoclave is in the heating phase the other is in the vacuum phase. When drying begins, the regenerated heat is used to preheat the water in the boiler circuit. Later on the regenerated heat is sufficient without the boiler. At the phase change-over the hot air from the heated autoclave passes to that which has finished its vacuum phase.

Autoclaves are made in diameters from 1.4 to 2 m with useful lengths from 4 to 8 m. Loading capacities are from 2.5 to 8 m3 per autoclave.

For producing the vacuum a liquid ring type pump is used while hot water or steam are produced by a boiler.

5.5 High frequency electric energy drying (or dielectric heating).

Much faith has been placed in the use of dielectric heating for drying wood: a) because with high frequency the moisture is heated

first due to its dielectric loss being above that of wood;
b) because heating is rapid and independent of the thickness of wood and is proportional only to the capacity of the energy concentration (heating rate reaches 20°C/min). The temperature gradient in the transverse section of the wood is the inverse of that with convection heating i.e. it decreases from centre towards surface layers due to superficial heat losses caused by evaporation and environmental dispersion.

Bringing the temperature of the wood and its moisture content to 100°C, the moisture inside the wood is transformed into steam. The steam pressure (also because retained by the moisture accumulated on the surface) increases with the progress of evaporation so that the steam is forced out very rapidly by way of the capillaries. The steam on the surface of the wood partially condenses, thus protecting it from excessive drying and the formation of costa.

When drying begins, with humidity above the saturation point of the cellular walls, the humidity gradient in the transverse section is the same as with convection drying. As drying proceeds, the gradient is inverted i.e. maximum humidity on the surface and minimum at the centre of the wood.

With dielectric heating four characteristic phases can be noted:

- phase I is pre-heating with maximum specific heat consumption. In this phase only the moisture in the wood is heated. The rate of heating is from 4 to 20°C/min according to the generator power;
- phase II is the equalization of wood and moisture temperatures which must be achieved before the latter reaches boiling point. Heat consumption in this phase, which corresponds to vapourization, is minimal;
- phase III is the evacuation of moisture in the form of steam during which the major part of the thermal energy will be consumed. Rate of evacuation can be very high, if the capillarity of the wood is continuous, because steam is formed in the centre of the wood with a corresponding increase in pressure. Therefore the rate will depend on the permeability of the wood and will vary, from one kind to another, between 0.1-1.5% min;

- phase IV is the equalization of the humidity of the wood to that required and during this phase energy consumption is minimal.

Drying time depends very little on the initial humidity of the wood. It depends very much, however, on the type of wood and the energy available, because the more humid the wood the more permeable it is.

Due to large surges in the consumption of thermal energy from phase to phase, the designing of plants and processes tends to favour the system of continuous feed of wood into the drier, resulting in greater economy because the generator output remains constant. A system of this type is shown schematically in Fig. 9.

The planks, loaded on a continuous belt, pass through a tunnel between electrodes. The moisture and steam which leave the wood (heated to 100°C) are dispersed in the air which, heated by the high frequency generator tubes, circulates through the tunnel and is finally extracted by a fan.

The output capacity of a standard plant is 25 kW (input 45-50 kW).

With this type of plant only permeable woods can be successfully dried: Beech (without false heartwood), Poplar, Limba, Abura, Agba, Lime, Spruce, Birch, Maple, etc. Drying times for 50 mm assortments vary from 2 to 4 hours (Beech planks pass from 80 - 90 % humidity to 6 - 8 % final humidity in 3 hours). The drying if tylosed woods and heavy dursmen woods, and therefore impermeable (Oak), is not very successful, With these types the centre of the wood, due to evaporation, dries quickly while the other layers remain moist. In this way the central temperature increases until collapse and carbonization occurs. To prevent this inconvenience, experiments in drying have been carried out in England by varying the primary voltage; but this method can only be successful with contact electrodes.

For untylosed and otherwise impermeable woods, the continuous tunnel process is not applicable. In that case a combined drying method can be applied with stationary convection drying inside the chambers with the centre temperature maintained besides that of the air circulating by means of high frequency.

Table 1

Table of the British Timber Institute (FPRL - Princes Risborough) on the humidity equilibrium of wood-air and on shrinkage and swelling in the humidity range from 60 - 90 %

Wood Specie	Equilibrium moisture to relative humidity of air		Shrinkage - swelling %				Dimensional instability	Deformability
			Tangential		Radial			
	90 %	60 %	between 60% and 90%	for 1% humidity	between 60 % and 90%	for 1 % humidity		
1. Obeche (Wawa)	19	12	1.25	0.18	0.8	0.12	0.30	1.5
2. Afrormosia	15	11	1.3	0.32	0.7	0.17	0.49	1.9
3. Maple	23	13.5	2.8	0.29	1.4	0.15	0.44	1.9
4. Birch	21.5	12	2.5	0.26	2.2	0.23	0.49	1.1
5. Beech	20	12	3.2	0.40	1.7	0.21	0.61	1.9
6. Oak (Europe)	20	12	2.5	0.31	1.5	0.19	0.50	1.6
7. Ash	20	12.5	1.8	0.24	1.3	0.17	0.41	1.4
8. Iroko	15	11	1.0	0.25	0.5	0.12	0.37	2.0
9. Cherry	19	12.5	2.0	0.31	1.2	0.18	0.49	1.7
10. Larch (Europe)	19	13	1.7	0.28	0.8	0.13	0.41	2.1
11. Limba	18	12	1.3	0.22	1.0	0.17	0.39	1.3
12. Khaya grandif.	23	14	1.9	0.21	1.5	0.17	0.38	1.2
13. Khaya ivorensis	20	13.5	1.5	0.23	0.9	0.14	0.37	1.6
14. Mahogany (Swietenia)	19	12.5	1.3	0.20	1.0	0.15	0.35	1.3
15. Makoré	19	13	1.8	0.30	1.1	0.18	0.48	1.7
16. Bété	20	12	2.3	0.29	1.3	0.16	0.45	1.8
17. African Walnut	18	13	1.3	0.26	0.9	0.18	0.44	1.4
18. European Walnut	18.5	11.5	2.0	0.29	1.6	0.23	0.52	1.3
19. Red Oak	18.5	11.5	2.4	0.34	1.3	0.19	0.53	1.8
20. Elm	22	13	2.4	0.27	1.5	0.17	0.44	1.6
21. Sapele	20.5	13.5	1.8	0.26	1.3	0.19	0.45	1.4
22. Teak	15	10	1.3	0.26	0.8	0.16	0.42	1.6
23. Wengé	15	11.5	0.9	0.26	0.65	0.19	0.45	1.4
24. Abura		11.5		0.20		0.08	0.28	2.5
25. Sipo				0.20		0.15	0.35	1.3
26. Kossipo		15		0.18		0.13	0.31	1.4

Table 2

Recommended final moisture content of wood for various products

	%
Commercially sawn timber	16-20
Timber for building purposes	12-18
Timber for sheds	12-15
Panels (plywood, particleboard, etc.) veneers	6- 8
Commercial veneers	12-16
Particle board cores	6- 7
Door and window frames (external)	12-15
Door and window frames (internal)	8-10
Internal parquet and matchboarding	6- 8
Internal furniture and furnishing in general	6-10
External furniture and implements (garden,etc.)	12-16
Coachwork and agricultural machinery	12-18
Coachwork for cars	7-10
Railway coaches (internals)	6- 8
Aircraft	6-10
Boats	12-16
Sports goods	8-12
Toys for internal use	6-10
Toys for external use	10-15
Wood moulds	6- 9
Rifle butts	7-12
Electrical accessories	5- 8
Musical instruments	5- 8
Wood dies	6- 8
Picture frames	6-10
Casks, packing cases	12-16

Table 3

Saturation pressure and humidity of air at various temperatures

Temperature in °C	Saturation pressure in mm Hg	Saturation moisture in g/m3	Absolute saturation humidity in g per kg of dry air
10	9.2	9.4	7.6
20	17.5	17.3	14.7
30	31.8	30.4	27.2
40	55.3	51.1	48.8
50	92.5	82.1	86.2
60	149.4	130.1	152
70	233.7	198	276
80	355.1	293.9	545
90	506.8	423.1	1400
100	780	600	dry air absent

Graph on Lumber Drying (Air Movement)

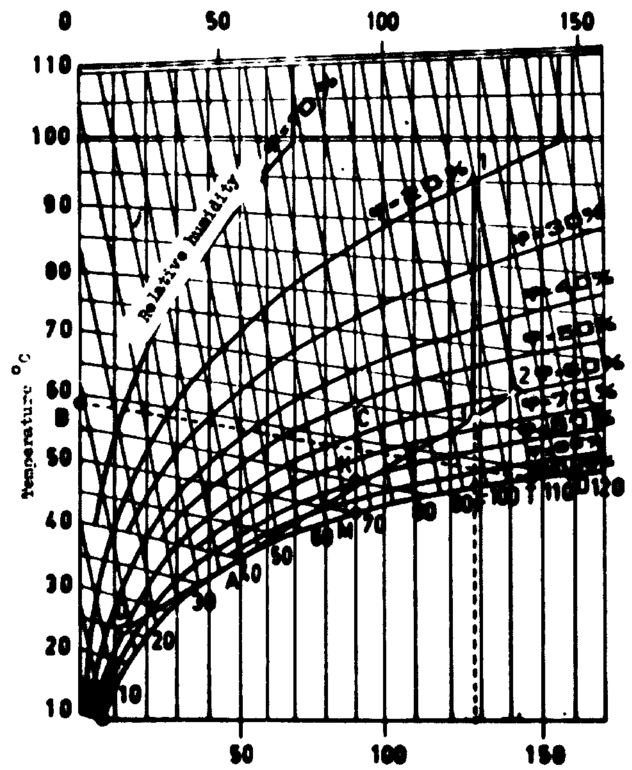
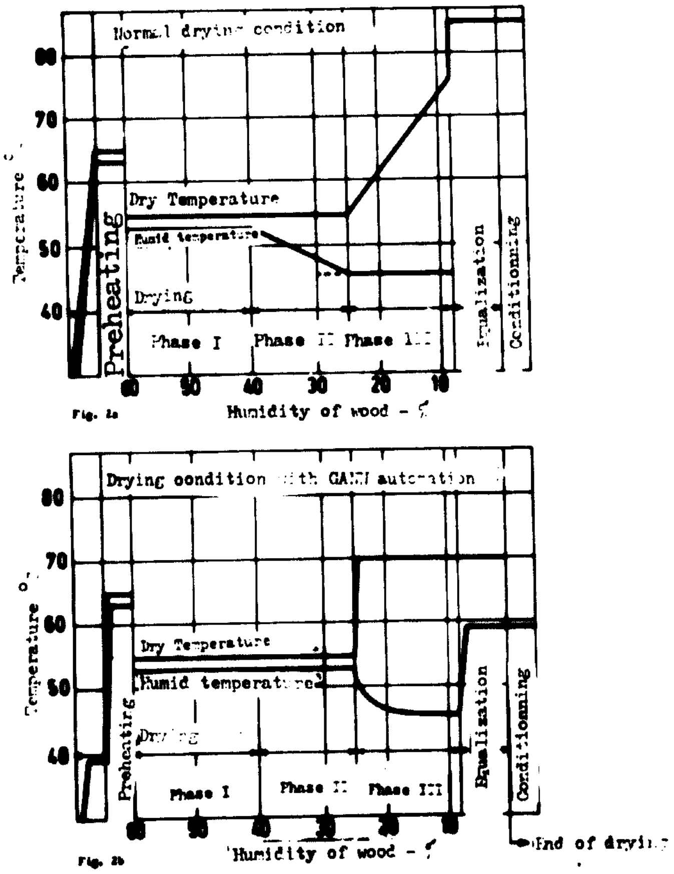


Fig. 1

Vapour pressure in kg/m^2 - Temperature °C

Relative humidity - Absolute humidity

Drying Conditions Graphically Indicated by Psychrometer and Electronic Control



Figs. 2a and 2b

VARIOUS MAKES OF CHAMBER TYPE KILNS

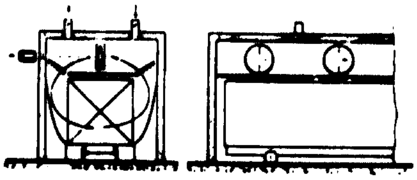


Fig. 3a

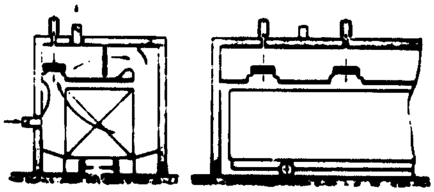


Fig. 3b

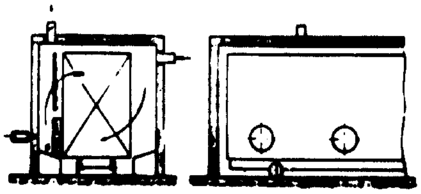


Fig. 3c

Fig. No.3a, 3b, 3c

VARIOUS MAKES OF CHAMBER TYPE KILNS - THE TYPE AS INDICATED BY Fig. 4d TO BE USED WHEN DRYING LARGE QUANTITIES OR LARGE TIMBERS

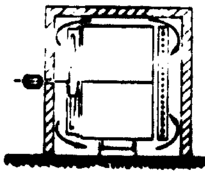


Fig. 4a

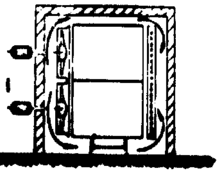


Fig. 4b

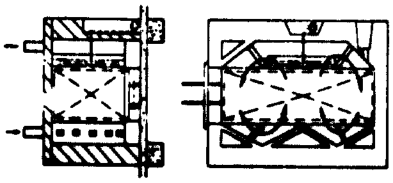


Fig. 4c

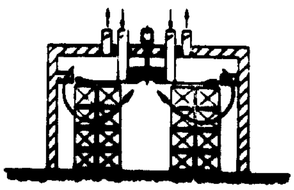


Fig. 4d

Fig. No. 4a, 4b, 4c, 4d

Schematic of technological process of periodic air drying (in chamber)

Left: Recirculation and conditioning of air by heating and partial air exchange regulated by shutters in the ducting.

Right: The drying process is represented by the trace I-2, partial air exchange by traces 0-3 and 2-3, heating by trace 3-1.

The preheating process for the purpose of bringing the air from point 0 condition to point I condition, and at the same time heating the wood, is represented by the cross-hatched section.

air recirculation
shutter
humid air outlet
fan
heating unit
external air inlet
psychrometer
wood

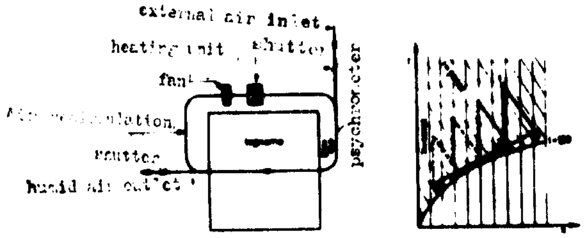


Fig. 5

Schematic of continuous drying process (in a tunnel) by longitudinal recirculation.

Right: drying process represented by traces 1-2, 2-3, 3-4 etc., according to the number of piles; reconditioning of the air is represented by traces 0-5, 4-5, 5-1.

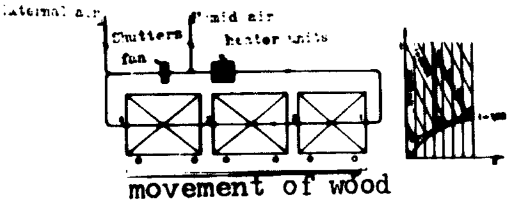


Fig. 6a

Schematic of continuous drying process (in a tunnel) by transverse circulation of air through coils.

Left: circulation of reconditioning of air;

Right: drying procedure represented by traces 1-2, 3-4, 5-6. Traces 0-1, 2-3 represent air reconditioning before it enters the piles, in each phase, with heating only.

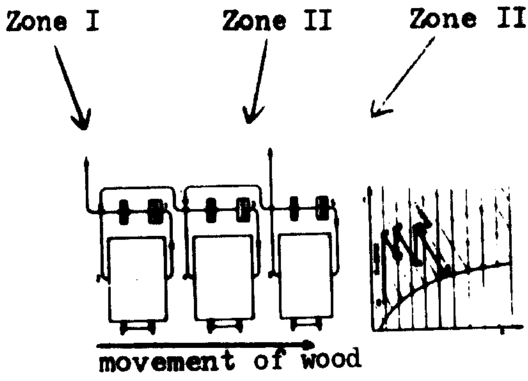


Fig. 6b

Schematic of continuous technological drying process (in tunnel) with transverse circulation of air.

Left: circulation and air reconditioning and movement of wood.

Right: changes in the air between the various zones of the tunnel. Drying is represented by traces 1-2, 4-5, 7-8. Traces 2-3, 0-3, 1-3 represent the reconditioning of the air in Zone I with the addition of external air (trace 0-3); traces 5-6, 2-6 and 4-6 in Zone II with the addition of part of the air coming from Zone I (trace 2-6) and similarly in Zone III, etc.

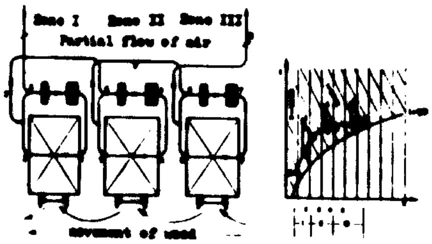


Fig. 6c

Schematic of Swedish Tunnel Drier
with Partial Recovery of Heat Contained in Exhaust Air

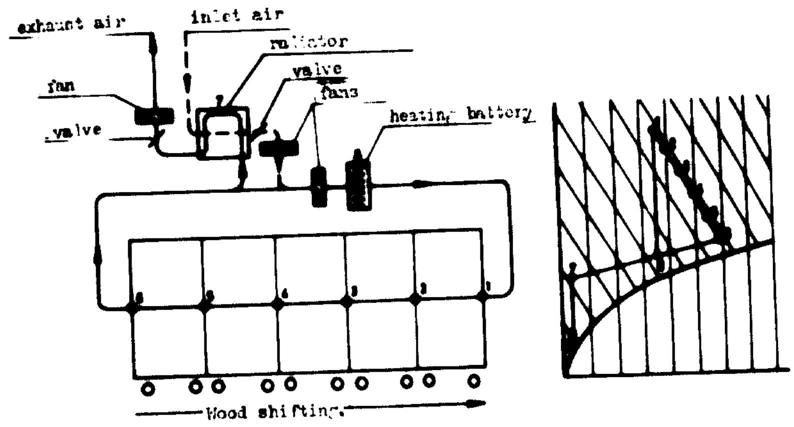


Fig. 6d

SCHEMATIC OF DRYING BY CONDENSATION

(a) air recirculating through the conditioner; (b) part of the recirculating air inside the chamber; (c) outlet of water condensed from the air; (d) conditioner: (e) fan

Traces on graph i-x: 1-2 drying; 2-3 cooling with condensation (the amount of condensed water corresponds to x); 4-6 heating; 5-1 mixing with air recirculating inside the chamber.

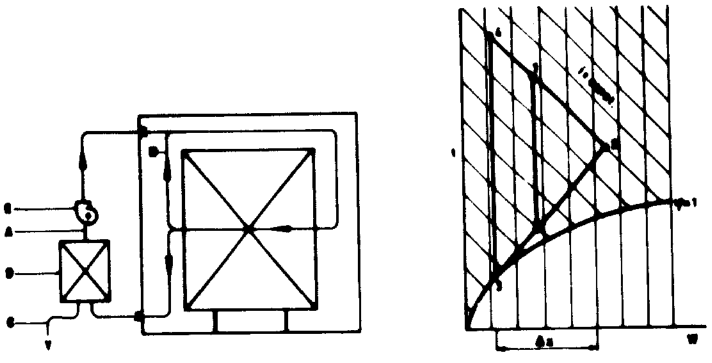


Fig. No. 7

SCHEMATIC OF CONDENSATION DRYING PLANT

(1) compressor; (2) condenser; (3) expansion valve:
(4) evaporator; (5) supplementary heater

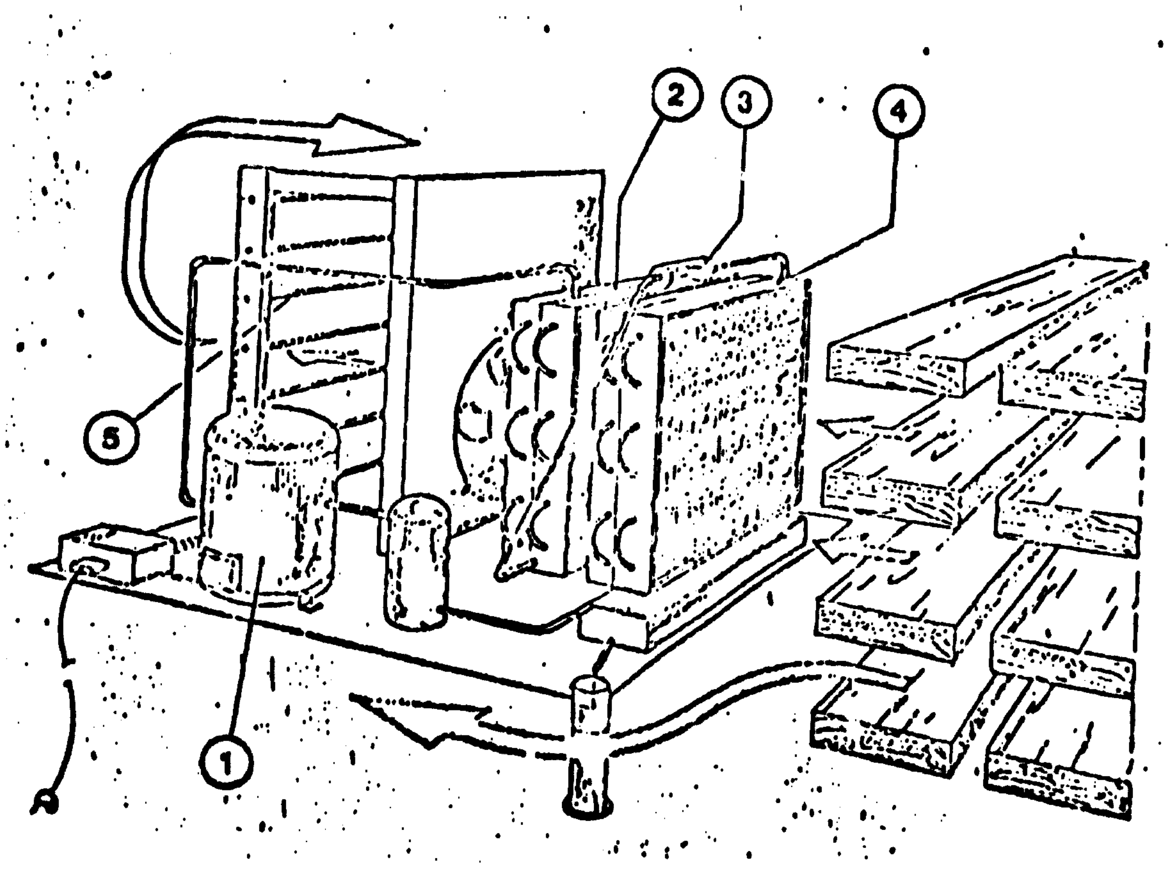


Fig. No. 7a

General Schematic of a Vacuum Drier

(1) heating system; (II) cooling system;
(III) vacuum punp unit

(1) autoclave; (2) boiler; (3) vacuum punp; (4) condenser water feed.

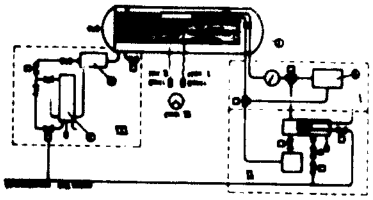


FIG. 8a

Functional Schematic of Vacuum Drier with Wood Heated by Recirculating Air

(1) autoclave; (2) cavity for circulation of hotwater and steam; (3) external insulating jacket; (4) boiler; (5) pump for hotwater circuit; (6) liquid ring vacuum punp; (7) heat exchanger; (8) oil separator; (9) fans; (10) boiler circuit; (11) recovery circuit; (12) ducting for air and steam evaporated from the wood.

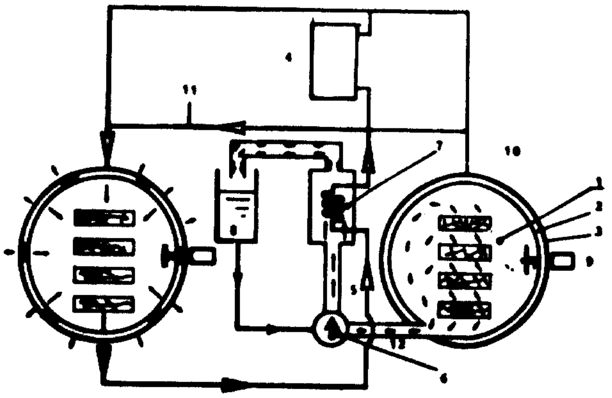


FIG. 8b

Schematic of High Frequency Drier

1) Conveyor belt

2) Electrodes

3))
) Air ducts
4))

5) Feed motor

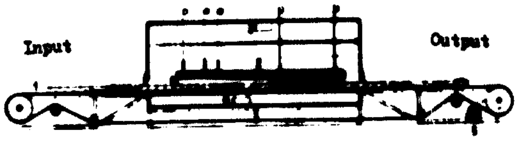


FIG.9

I - 85

▽

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