Environmental pollution reduction by using VOC-free water-based gravure inks and drying them with a new drying system based on dielectric heating

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Chapter 1
General Introduction

1.1 Introduction

A successful package begins with a good design and needs an appropriated science-based technology. The first examples of packaging are actually delivered by the nature, as for example a banana leaf. Later were used for thousand of year's amphora or different packages made with natural products as leather or wood. Today, the technical evolution and the scientific revolution have lead to packages as aluminum can and bubble pack. Originally, main purpose has been to preserve goods, especially during the transport. Today, the packaging process remains necessary to transport food and other products from the producers to the consumers over longer distances, to store and preserve them, but also other aims have become relevant: give the information about the contents (ingredients, expiring date, etc.), with a design, including this printed information which has also become a powerful marketing tool.

The printing processes are very important for completing the packaging processes. The design of printed packaging materials reflects the personality of the product, its philosophy, and the taste of the firms who have created them.

There are seven major methods of printing processes: Letterpress, lithography, gravure, flexography, electrostatic printing, silk screen printing and ink-jet, but the wide spreaded printing processes for packaging are:

1. On plastic films: flexographic and rotogravure printing
2. On paper, paperboard and multilayer paperboard: flexographic, rotogravure and also sheet feed lithography.
3. Ink-jet is used mainly for information which may change as the expiring dates, manufacturing details etc.

Flexo and gravure printing are dominated in web printing for packaging and both of them are stable enough to be used in reel-to-reel web printing. In flexo-printing machine, the drying process must be completed between the last printing unit and the winding while it takes place in gravure-printing machine between every printing unit. This means that the drying must complete in fraction of seconds. Such a short drying time can be achieved by the following drying methods:

1. Evaporation of ink solvent
2. Radiation-curing of the ink.

Usually, evaporation of ink solvent method is widely used because it is inexpensive. Theoretically, radiation-curing inks could be also applied as they also dry in short time, but they are too expensive and have also another disadvantage, namely health hazardous, special precautions must be taken etc.

Flexo and gravure inks are low-viscosity liquids and they are similar in composition. They are consisting of colorants (dyes or pigments), binders (natural resins, artificial resins, or plastics), solvent or solvent blend and additives.[1]

Commercially, these inks are available in two main types: solvent-based and water-based. Solvent-based flexo inks primarily contain alcohols and esters as volatile organic compounds (VOC) with concentration ranging from 50% to 70% at print viscosity. Different solvent mixtures are used depending on substrate types, end-use applications, and type of presses. These solvents must have a low boiling point because they should dry at low temperature so that the paper and plastic substrates are not damaged by heat which is applied in dryer ovens in the printing machine.

As a result of drying processes a VOCs will be released to the air circulating in the dryer and without treatment (filter or afterburners) there would be a significant source of pollution from most printing operations. The main disadvantage of pollution treatment is that it is an expensive process (it needs further equipment and consumes energy).
The Environmental Protection Agencies in US, Europe, Canada, and many other countries have restricted the amount of solvent that can be released into the air to reduce the pollutants released to the environment by the printing industry.
The solvents are not evaporated completely; some amount is retained in the ink and being released slowly, which is an inherent health problem and has negative effects in the perception of aroma and taste of the food contents of the package. Therefore, there is a growing demand to make use of of water based inks.

Water-based flexographic inks have partially replaced the traditional solvent-based inks especially in food packaging. The water-based gravure inks are being used on flexible films and publication printing in the US, Japan to reduce VOC emission.

The water-based inks are not completely free from VOCs. The water-based inks usually contain:

- Low levels of solvent, mainly alcohol, to improve the adhesion on the plastic films and foils in addition to increase its wettability.

- Little amounts of ammonia and/ or amines to achieve a permanent drying of the ink film.

Water-based inks in flexographic and gravure printing have the following advantages:

1. Reduction of VOCs emitted to the atmosphere.
2. Reduced potential for discharging toxic substances into the water system.
3. Reduction of the potential for fire and explosion, thereby eliminating some of the costly provisions and regulations required for flammable solvents and inks.
4. Reduction of the amount of hazardous wastes.
5. Improvement of the working conditions in the plant.
6. Compliance with almost every regulation for firms using these inks.

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[1] Sam Gilbert, ”Flexographic Inks” in Coating technology handbook, Marcel Dekker, Inc, 1991, PP 593-595.

Despite of the above mentioned advantages, the water-based inks suffer from the following inherent technical problems:

- Poor freeze-thaw stability.
- Resolubility: sometimes referred to as drying out on the press, this requires a careful balance between the alkali-soluble (Ammonia and amines are there in the alkali) and the emulsion polymer.
- Formation of foam during the printing process.
- Drying problems, approximately four and half times slower than the solvents.

Drying of water-based inks has more technical difficulties compared with drying of solvent-based inks. Some of these problems are listed below:

1. With a inhomogeneous distribution of ink in printing area and using a conventional drying system the differences in the moisture of paper remains, because of the need of drying of the printed surfaces may cause over-drying of the non- printed areas. And after the process of folding, it becomes a bit difficult to keep it in the wished lateral position and with the required tension of the web.

2. Owing to the longer evaporation time of water from the ink longe-lengthy dryers are needed compared with the dryers used for organic solvent-inks.

3. With non-hygroscopic substrates such as plastics films, the non- printed areas may be heated over the glass point, with a degradation of the mechanical properties as a result of using longer drying time.

1.2 Aim of the study

As mentioned above, one of the main problems in using water-based inks in packaging printing is the conventional drying process where it needs longer time and it might damage the non-hygroscopic substrates and over-dry hygroscopic ones.

Longer drying times leads to higher energy consumption, slowing down the printing process (40% - 50% slower as with solvent based inks) in addition to negative effect of the physical properties of the printing substrates.

The aim of this study is to overcome the above mentioned drying problems of the water-based ink in packaging printing. To achieve this target we have done the following:

1. Constructing a novel microwave dryer for water-based ink to reduce the drying time and consumption of power in addition to keeping the substrate physical properties unchanged. The drying of these inks after printing with a new drying system (microwave plus air convection) where the heat is released only in the wet (printed) areas, without thermal effects on the substrate in the non-printed areas, actually giving the needed evaporation heat directly to the water molecules in the ink film, but not to those in paper substrate.

2. Using VOCs free water based inks enhanced by laminating the printed surface with water-based lacquer.This water based lacquer has a little amount of ammonia which is released when they dry irreversibly. As a lacquer must only wet, without being necessary other printability properties, amines are not needed, with a limited amount of ammonia may be enough; ammonia is a simple and cheap chemical which can be separated easily from the exhaust in a washer and then be fixed.
   As substrate is paper a suitable material; paper is composed mainly by cellulose fibers obtained from wood, this means that a renewable raw material. In addition to fiber papers generally contain sizing materials, mineral filler, and coloring matter. Another water based lacquer may be applied to the internal side of the paper, according to the packaged product.

3. Confirm that the time for dimensions change of the paper after printing with water based ink in the order of magnitude of seconds, as reported by printing plant operators.
   The slow change of dimensions of the paper after printing with water based ink means that it would be possible with microwave dryer to evaporate the water of the ink before much dimension change occurs.
   The academic world knows only the times for dimension change after wetting the paper with water, in the order of magnitude of seconds.

As well known 27.12 MHz high frequency dryers possess the same physical principles as microwave dryers and have the same advantages. High frequency drying did not find certainly a brother application because the equipment, especially the 27.12 MHz generators are too expensive. Therefore, in this study working at a frequency of 2.45 GHz magnetrons, this means the same frequency at which kitchen microwave ovens and many thermal industrial microwaves equipments are operated. This 2.45 GHz magnetrons may be used as high frequency power sources; they are produced in large quantity and therefore to accessible prices.

Chapter 2

Drying methods of the printing inks

2.1 Introduction

Printing inks consist mainly of binder, pigments or dissolved dyes and solvents as volatile organic solvent or water.

Inks should remain liquid and with the ability to wet the substrate up to the transfer to the substrate, once on the substrate they should dry, this means become solid, at least rub resistant, as soon as possible.

This means, the printing inks structure must be adequate to rapid drying and anchoring on the substrate after printing and drying, in the same time avoid to drying on the press during press operation or short standstill periods.

There are different drying mechanisms of the printing inks, which may be depending upon the following factors:

1. Printing method (offset, gravure, flexography, etc.)
2. Printing inks type (liquid, paste, water or organic solvent based, radiation curing inks, etc.)
3. Speed of printing machines.
4. Printing materials substrates (paper, foils, plastics, etc.)
5. The type of the printed product (packaging printing, commercial printing, etc.)
6. The characteristics of the dryer systems (hot air, cured systems, IR, etc.,)

As well known, depending on the ink formulation drying is effected either by chemical reaction (oxidation or polymerization) or by physical processes (penetration, evaporation) or by a combination of both.

Gravure, flexography and web offset inks dry primarily by evaporation. Inks for sheet fed offset (not rubber based) generally dry by oxidation polymerization, the heat set inks dry by evaporation in hot air dryers. Also may be found combination of two or more drying system to achieve the final drying of the ink film.
In this chapter the common drying mechanisms will be explained, which are used for drying the most known ink systems.

2.2 Absorption drying

Ink dried by absorption when printing application complete on absorbing surface such as newspaper print or corrugated board[2]. The ink structure is obtained mainly by penetration of liquid components into the substrate and sucked up into the paper by paper capillary tubes, leaving a dry to handled ink on the surface.

Generally, this type of drying method is depending on the carrier viscosity of the printing ink, the vehicle (binder) and the absorption capacity of the substrate.
The printing ink components start penetrating with the transfer of the printing ink onto the paper as shown in Figure 2.1, and then they are sucked up into the paper by paper capillary tubes.[3]

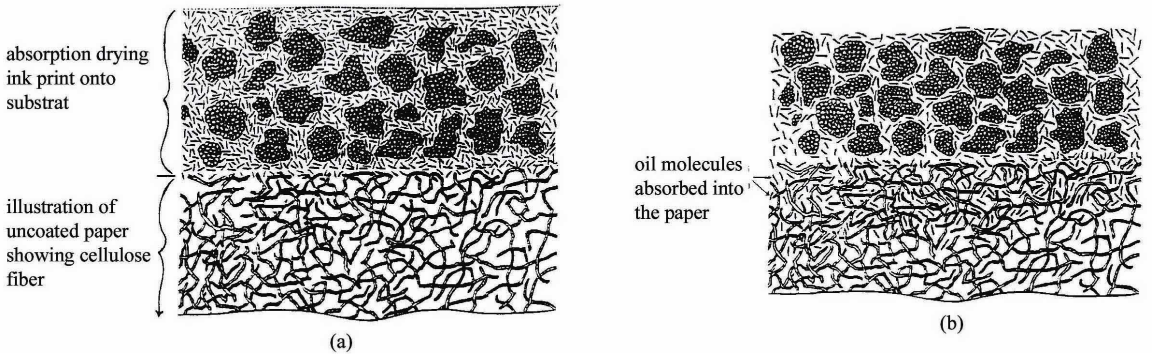

Figure 2.1: Absorption drying mechanism
(a) Ink just printed
(b) Ink nearly dry

The inks will have an absorption mechanism when applied to absorptive substrates even if the eventual main drying procedure is completed by an additional method. For example, in offset printing on absorbing substrates, inks first dry by penetration and then the final drying is accomplished by oxidation and polymerization.
The absorption helps in the setting or drying of other inks such as in quickset inks which have high viscosity varnish and low viscosity oils, the drying is completed when the paper absorbed the oil, as consequently viscosity rises rapidly. This drying method is used only for offset or letterpress inks on porous substrate as in newspaper printing.

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[2] Terry Scarlett & Nelson R. Eldred, what the printer should know about ink, GATF, 1984, PP.77-78.

[3] Helmut Kipphan, Handbook of Print Media Technologies and Production Methods, Springer Verlag, Berlin Heidelberg New York, 2001, P.166.

2.3 Oxidation polymerization drying

This type of drying system depends on the chemical reaction between the oxygen from the atmosphere and the drying oil (such as linseed oil, china wood oil, or Soya oil) within components of the vehicle system. The result of this process is converting the ink film on the substrate to a semi-solid or solid.

The oxidation polymerization mechanism accomplished as the following:

1. The oxygen in the air adds to double bonds of the drying oil molecules to form hydro-peroxides.
2. In presence of an initiator or catalyst (cobalt or manganese salt) the result is that the hydro peroxides form free radicals which are very reactive, these attack other molecules and attach forming new (large) free radicals, this causes polymerizations.
3. Since many of the molecules have multiple reactive sites (i.e. double bonds) some cross linked are formed creating a network (Figure 2.2) and then the ink film has been dried after some hours.

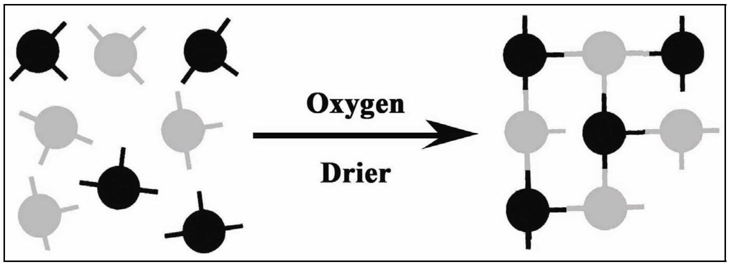

Figure 2.2: Oxidation Polymerization drying mechanism

It should be supplied with sufficient oxygen in the delivery pile to achieve cross-links of the ink layer on the printed substrates. Therefore, the necessary space between the sheets can be increased by powdering to achieve of oxygen diffusing in the piles.
The main applications of this drying method are in sheet fed offset on the porous substrates as coated paper and plastics.
The essential problem in this type of drying is the long time 2-4 hr.needed to a complete drying ink film before folding and cutting or finishing process.

2.4 UV and EB drying

Energy cured inks are ones which cure, or harden, under exposure to radiant energy. There are several types of radiation applied to dry the inks may be in form of UV light, infrared radiation, and electron beam (high energy electrons).
Whereas the IR radiation has no direct significance for chemical (oxidative) drying, it is merely the elevation of temperature that increases the reaction speed. However, UV radiation and ionizing radiation (electron-beam) in comparison produce radiation polymerization or cross-linking (chemical drying)[4].

2.4.1 The UV drying method

This drying method requires special inks containing:

1. completely different binders (vehicles may be acrylate compounds such as acrylated urethanes, acrylated epoxies, and acrylate monomers)
2. additional photo-initiators (may be aromatic ketones or esters, acetophenones, benzoic derivatives or benzyl ketals) its functions as a UV-light antenna which absorbs the energy of the UV- light photons and the result is spontaneous decomposition of the photo-initiator into highly reactive fragments called radicals. These fragments initiate a chain of polymerization with great speed, resulting in a polymerized solid film.

As well known above, these inks dry or set by an acrylic polymerization which is very quick. Not like in the drying by oxidation which need many hours to complete drying of the ink film, this reaction is complete in a fraction of a second. This means in few seconds, prints are ready for the finishing process, no spray powder is required to prevent setoff.

Conventional UV dryers work with one or more mercury vapor lamps[4] . The wavelength range lies between 100 and 380 nm[5]. The system is enclosed by reflector housing as shown in figure 2.3(a and b)[6]. Optimum cooling and extraction of generated ozone is necessary for the complete system.

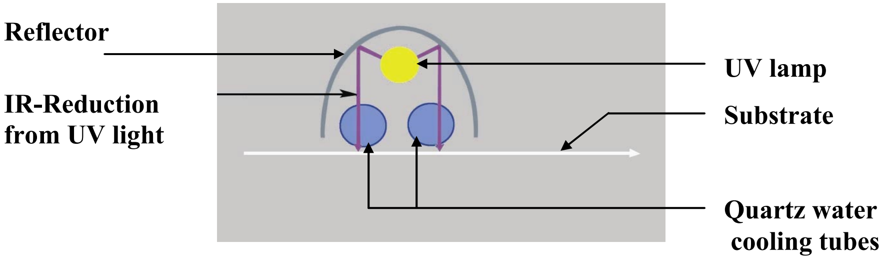

Figure 2.3 (a): Ultraviolet lamp curing, including one fitted with water cooling

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[4] F. Schroeder, strahlenvernetzbare Beschiftungssysteme, FARBE+LACK , Jahrg. 93, 6/1987.

[5] Helmut Kipphan, Handbook of Print Media Technologies and Production Methods, Springer, Verlag Berlin Heidelberg New York, 2001, P.174.

[6] http://www.hoenle.com/eng/prod/uvaprint_acm.html

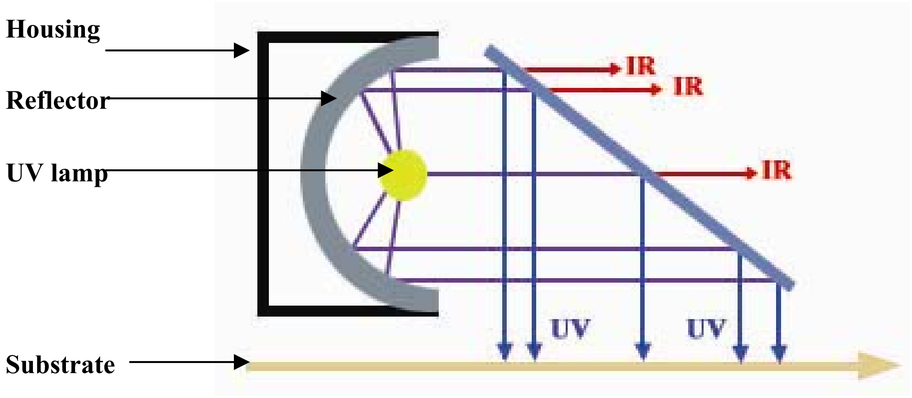

Figure 2.3 (b): Ultraviolet lamp system
Concept of the cold mirror technology

2.4.2 Electron beam drying:

This drying ink method is similar in composition to UV inks except that use of high-energy electrons to bring about a free radical reaction; this means the photo initiator is not necessary and therefore the storage stability of the inks is better. Because the oxygen from the air may be absorbing on the surface of the wet inks, the curing may be inhibited therefore, this is counteracted by passing the web through a chamber filled with an inert gas (nitrogen). An electrically heated tungsten ribbon serving as an electron-beam source is admitted to the web as shown in Figure 2.4.

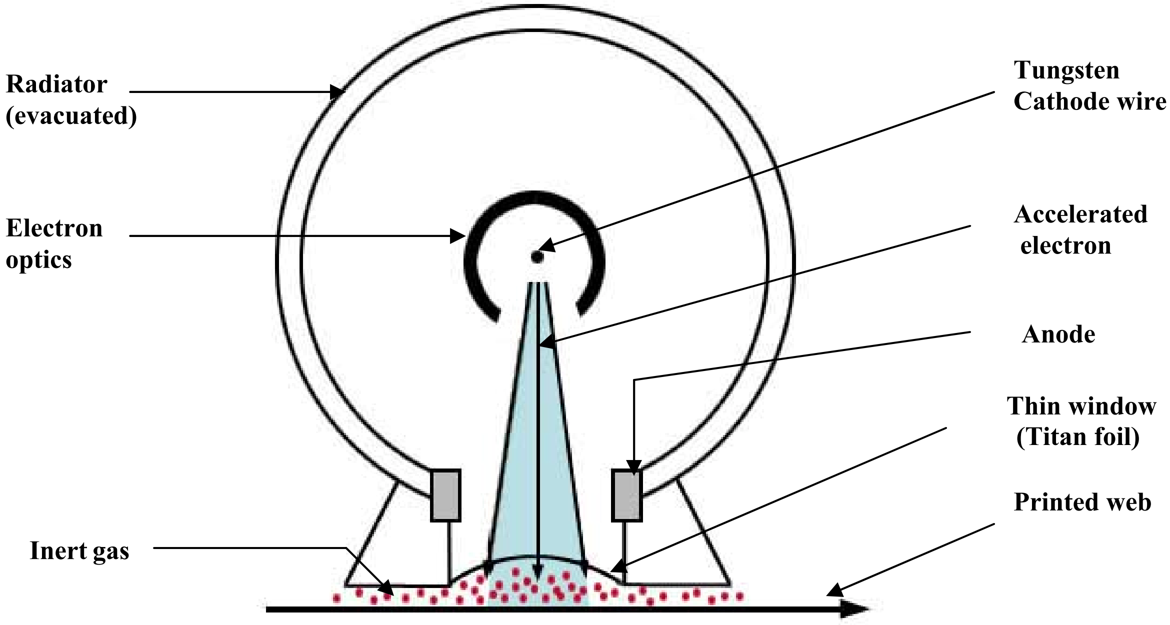

Figure 2.4: Principle of electron beam tube

In spite of these drying ink systems have advantages such as:

1. the use of 100% solid, solvent free, non-polluting systems
2. low fire hazard.
3. minimal space requirement compared with the conventional drying ovens
4. the UV inks or coating do not dry on coating and printing rollers, printing plates or cylinders.
5. in the EB mechanism there is no unwanted high heating of the substrate or the printing ink layer occurs
6. drying in a fraction of a second

However, they have still a lot of problems such as:

1. high capital investment due to accessory equipment.
2. high costs for printing inks, washing agents, etc. compared with conventional sheet- fed or web inks.
3. relatively short service life of UV lamps
4. pigmented and opaque systems may be difficult to cure (The color black prevents UV radiation from penetrating in the ink layer and the curing effect is less than with chromatic colors or varnishes)
5. in the EB mechanism, the substrate is possible to get damaged if the radiation dose is too high
6. The binder of the wet ink is composed by chemical active and health hazardous compounds which require special solvents to clean the press. Fore this reason special precautions must be taken.
7. special precautions are necessary to avoid danger to human beings from the curing radiation.
8. “De-inking” problems occur during recycling process for substrates which were printed with UV inks, which dry through a polymerization with a strong cross-linking[7].

2.4.3 Infrared radiation drying

Infrared drying is a technique employing four curing mechanisms: polymerization, oxidation, penetration and evaporation. Each of these mechanisms is based upon the efficient transfer of heat energy from the infrared radiation to the coated wet ink film.
As well known, there are three heat transfer modes:

- Radiation,
- Convection,
- Conduction.

On the hot air drying, the heat transfer to the wet ink film is achieved by the convection mode, while the most heat is lost to the heating oven (the web substrate and the air inside

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[7] Helmut Teschner, Offsetdrucktechnik , FachschriftenVerlag, 1997, PP.13-14.

the dryer). On the other hand, in IR drying system, the energy emitted by IR radiation is directly used for heating the wet ink film.

Infrared radiation may transfer large amounts of energy in short time[8]. As the wavelength of the infrared radiation is too long (much longer as the wavelength of UV-radiation), the energy of their photons is too low (much lower as the energy of UV-photons) to achieve any photochemical reactions.

This means that, with infrared radiation only a heating of the printed substrate is reached. Such a heating may be useful to:

1. accelerate the oxidation drying process, for example by using IR radiation drying, the drying time of the sheet feed inks can be reduced by around 80 % (but remain in the order of an hour or fraction of an hour).

2. as a heat source in evaporation dryers.

An important aspect of infrared heating is that the heating may occur without needing any mechanical effects like for example high-speed hot air jets.

This is relevant in sheet feed presses or, combined with either hot air or ambient especially to dry solvent-based inks or water based inks.

It is important to adjust the infrared wavelength to suit the absorption characteristics of the inks and substrates.

Actually, the IR is an extension of electric resistance heating since the electric IR emitters are heated by passing a current through a heating element; the element may be in glass tubes, quartz or metallic tubes, or in ceramic panels. The IR classified by its wavelength as the following ranges:

2.4.3.1 **Short-wave** (0.76–2 µm, equivalent to 2200-1100°C) this type has great penetrating power and is therefore capable of heating thick wet ink films, because it is not absorbed by air.

Shortwave IR radiation penetrates mainly into the paper; and more efficient in case of water based ink drying than medium wave, but the problem of which may occur is the damage effect of the printing material substrate (like poly-coated release paper and film, where excessive heat could damage the web or fabric) as the IR radiator heats, moreover because of the non-printed areas in the printed paper.

2.4.3.2 **Medium-wave** (2–4 µm, equivalent to 1100 -750°C), the air is heated mainly above the ink layer. It is also efficient in drying processes, which combine solvent evaporation, and chemical curing (cross-linking) of organic compounds in the wet ink film.

2.4.3.3 **Long-wave** (4 µm to 1 mm equivalent to 750 - 450°C), because it is readily absorbed by air and does not penetrate within wet ink films, therefore long wave radiators are not applied.

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[8] H. C. Wright, Infrared techniques, Oxford university press, 1973, P. 7.

Despite the fact of advantages for IR drying systems to accelerate the final drying mechanisms, this drying method has still some disadvantages such as:

1. higher investment leading to higher hourly rate of press due to the installation of the IR system.
2. using IR requires special precautions:
    a. to install extra emitters to ensure that dryer continues to perform well, since the lamps can burn out during production
    b. sufficient clean cooling air is necessary to cool the emitters especially the ends and bases of quartz tubes

3. higher energy consumption.
4. increased temperature in the machine as well as in the press room.
5. IR (shortwave) is very selective of color; that is: the black areas of an image are charred before the yellow beings to dry9.
6. in case of water based coating or inks which are printed on paper, the thermal effect of IR radiation coveres the whole areas (printing and non-printing areas) while the ink vehicle evaporating the moisture content in the non-printing areas decreases and may occur overheating problems and leads to problems in product finishing.

2.5 Evaporative Drying

There are several ink types which dry by the physical removal (evaporation) of the solvents or water in the wet ink film.
After the evaporation as shown in figure 2.5, the solvents leaving resins and other materials to bind the colorants to the substrate (paper or films) achieve rub-off resistance as possible.
This type of drying process requires airing in the function of amount of ink has been applied and function of the atmospheric humidity. Such drying can be accelerated by blowing hot or cold air over the surface to be dried very rapidly by evaporation of solvent or water.
As soon as, ink is coming to the next printing station, it must be dried to allow the printing machine running at high speed without any drying problems.

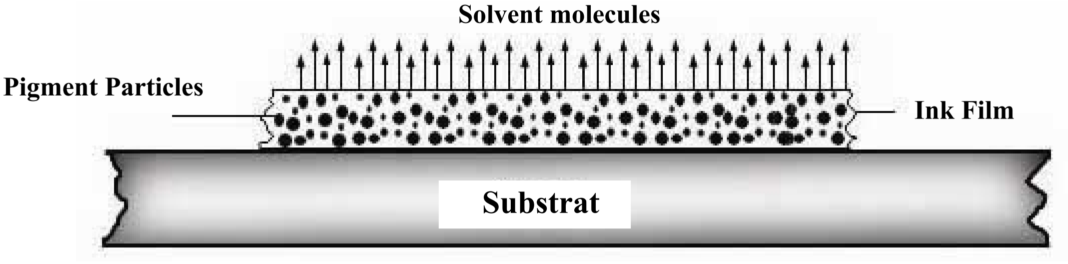

Figure 2.5: Schematic diagram of ink drying by evaporation of the volatile solvents, leaving a dry ink film on the printed stock

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[9] Terry Scarlett & Nelson R. Eldred, what the printer should know about ink, GATF, 1984, P.84.

The efficiency and speed of the evaporation process is determined by three factors[10] as the following:

- the rate of evaporation of the ink solvent.
- the chemical and physical interaction between the solvent and the other ink components.
- the rate of removal of the evaporated solvent from the surface of the ink film.

The evaporation drying mechanism are used in several printing methods for example, web offset (high boiling point mineral oils ink) and flexographic and gravure printing (low boiling organic solvent inks), with increasing of the efficiency of the drying process, it must combined with another drying mechanism such as IR heater to preheate the wet inks before entering in the drying chamber.

Despite of above mentioned facts the evaporation drying method still has some problems such as:

1. organic solvent based inks need high capital investments for accessory equipments for pollution control. The waste air from the dryer exhaust loaded with organic vapors must be cleaned before releasing it to the atmosphere.
2. Water based inks still use alcohol to enhance the ink wetting and the drying properties. Pollution control devices may remain necessary especially if ammonia and amine group are present in the ink.
3. to dry the water based inks with evaporation methods, a longer time is needed, because the drying is 4.5 times slower than with solvent based inks
4. higher energy cost
5. drying systems for water-based inks require considerable space to achieve complete drying; the paper web needs to remain in the drying area for 0.8 to 1 second. If the paper web travels at a speed of 8 m/s, the dryer needs to be at least 8 m long.
6. the probability for occurrence of overheating (cooking) of the printed web by the moisture loss from the non-printing areas of the paper substrate may cause register inaccuracy, and variations of the visco-elastic properties of the plastic substrates. Thereby, the print finishing processes become more and more difficult.

2.5.1 Principle of evaporation drying

With water as solvent in the inks, the basic process of evaporation in which the heat is transferred from the surroundings into the wet ink film after printing immediately on the substrate, as a result the ink solvent vaporize, and by air movement this vapor is carried away from the dryer. The time required to evaporate the ink solvents is based upon:

- the amount of solvent (water or organic solvent) to be dried (i.e. thickness of coating and solvent percentage of inks and coating)
- The evaporation rate

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[10] Cecilia Christiani; GFL & J.Anthony Bristow; STFI, The drying mechanism of water-borne printing inks, TAGA's 47th Annual technical conference, Orlando, Florida, April 1995, P. 7.

The evaporation rate is dependent upon the vapor pressure difference between the water in the ink layer ($P_{surface}$) and the air being circulated over the surface of the part (P_{air}). There are several methods to increase the difference in the vapor pressure as the following:

1. decreasing the humidity of circulating air.
2. increasing the temperature of circulating air.
3. increasing the temperature of the ink and coating.
4. increasing the velocity of air across the substrate surface

Precisely, the drying process consists of:

1. putting energy into ink (heat transfer),this energy must be emitted from the dryer chamber and transferred to the wet layer
2. removing away the water as vaporizes from the dryer (mass transfer).

This means the released water must be evaporated to surrounding air, and then removed away from the dryer chamber by the air circulation.[11]

The heat transfer rate to the wet ink is proportional to the printed area, and the temperature difference, which can be established between the cool surface and the hot air as the following[12]:

$$\dot{Q} = \alpha \cdot A \left(t_{air} - t_{surface} \right) \quad \text{watt/sec} \qquad (2\text{-}1)$$

Where

$\dot{Q}$: is the rate of heat transfer in watt/second

α : is coefficient of heat transfer $\left(\frac{W}{m^2 \cdot K} \right)$

A : is the printed inked area in m^2

Heat transfer that is implanted in the wet ink film is followed by mass transferring action to dry a wet ink layer via raise the temperature of wet layer to its evaporation point- mass transfer as following:

$$\dot{m} = \sigma \cdot A \left(P_{surf} - P_{air} \right) \quad \text{kg/sec} \qquad (2\text{-}2)$$

Where

$\dot{m}$: evaporation rate (mass of the liquid is transferred away from the printed Web) in kg/h,

σ : Mass transfer coefficient,

P_{surf} : saturated vapor pressure at the ink surface

P_{air} : Pressure of air above ink layer

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[11] Joseph Black, Evaporative drying of ink, using high- velocity air jets, Journal of the institute of printing , vol 22, No 1, Jan 1978,PP 12-15.

[12] Frank P. Incropera & David P. Dewitt, Fundamentals of Heat and Mass Transfer, John Wiley& Sons, Inc, 2002 , P.6.

Drying rates are specified in the quantity of water from the ink that can be evaporated per m^2/h, Heat in 2-1 and Mass out 2-2.

Therefore, when the printed web goes through the dryer which heated up to evaporation temperature, the vaporization of the wet ink areas will occur and the temperature is reduced.

2.5.2 The effect of air velocity

To understand the evaporation drying process in the modern dryers, it is necessary to explain the role of the "boundary layer" [13].
The air flow in the dryer shows a strong turbulence, but this turbulence can not reach to the surface of web. The flow in the last millimeter or fraction of a millimeter to the surface of the web remains laminar this means the layer immediately above the printed web is a boundary layer (laminar- buffer zones). This means the boundary layer is a mechanism which governs the heat and mass transfer for drying.

The significance of boundary layer behavior in modern dryers is that the boundary layer tends to act as a barrier to the transfer of heat from the fluid to surface of the printed substrate and to the transfer of solvent vapor from that surface to the hot air.
Therefore, the effects of air flow in the modern dryer are[14]:

1. improvement in transfer of heat from the hot air flow to the printed web which is being dried
2. removal of residual solvent vapor from the surface of the boundary layer, permitting further diffusion of solvent from the printed substrate surface, through the boundary layer
3. reduction in thickness of the boundary layer increases the rate of solvent diffusion from the web surface to the main air stream which carries the solvent into the dryer exhaust.

As shown in Figure 2.6, the relationship between air flow (velocity) and boundary layer thickness is not a linear relationship, this means with increasing air velocity the boundary layer thickness decreases.

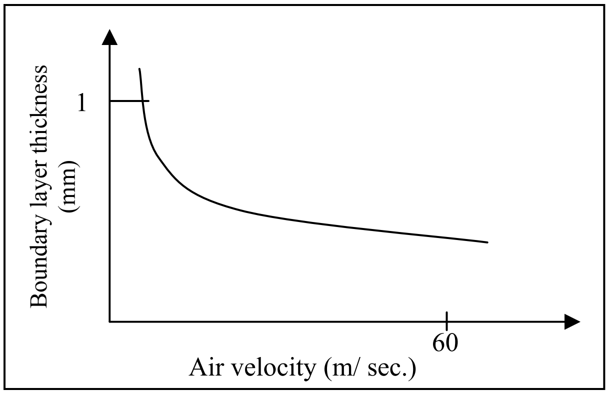

Fig. 2.6: The effect of air velocity on Boundary layer thickness

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[13] David B. Crouse & Robert J. Schneider, Web offset press operation, GATF,1989, P.73.
[14] P. Laden, Chemistry and technology of water based inks, Chapman & Hall,1997, PP.98-99.

The heat transfer rate rises rapidly and continues to increase with increasing air velocity as shown in Figure 2.7.

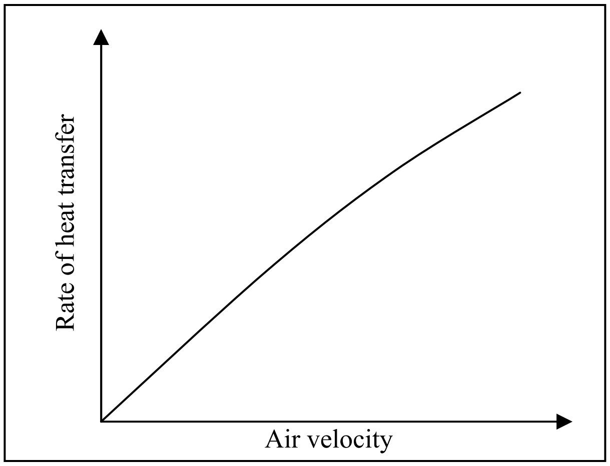

Fig. 2.7: The effect of air velocity on rate of heat transfer

2.6 Radio frequency (RF) drying

In the radio frequency drying system, the RF generator creates an alternating electric field between two electrodes as shown in Figure 2.8. The frequency 27.12MHz is the mainly used frequency.

The material to be dried (for example glue, inks and paper, carton or others) is conveyed between the electrodes where the alternating electric field causes polar molecules in the material to continuously re-reorient themselves to face opposite poles such like the way bar magnets behave in an alternating magnetic field. The friction resulting from molecular movement causes the material to rapidly heat throughout its entire printed ink film[15].

The amount of heat generated in the material to be heated can be determined by the frequency, the square of applied voltage, dimensions of product and the dielectric loss factor of the material, which is essentially a measure of the ease with which the material can be dried by RF waves. Principle of the radio frequency drying method is quite similar to microwave drying which will be described later. An effective RF dryer must include some air flow to take away the evaporated water.

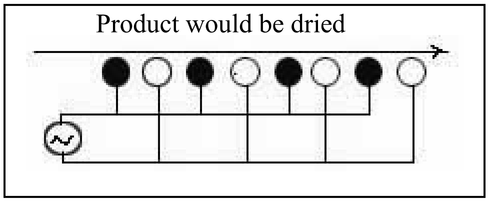

Fig 2.8: depicts RF drying system, the product passing over electrode array

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[15] Peter Henschel, Radiofrequenuenz-technologie erlaubt steueruung einer Medium-bezogenen trocknungsintensität,Papier+Kunststoff-Verarbeiter vol No.10-1984, PP.56-58.

Chapter 3

The printing inks and the environment

3.1 Introduction

The environmental pollution can be defined as substances or energy introduced by man directly or indirectly into the environment, which leads to result harmful effects of such nature as to endanger human health, harms living resources, ecosystems, and impairs or interferes with amenities and other legitimate uses of the environment[16].

The residual pollutants can be classified according to various criterions; for example, according to physical conciliations and chemical composition or according to the effects of the discharges. So the main types of these residuals are[17]:

a) Material residuals: Solid, Fluid, Gaseous
b) Energy residuals: Heat, Noise (transformed to heat), Radiation

Because the atmosphere and water around us are in a state of constant movement and the pollutants that are released into them in one region may eventually spread to the rest of the world.

Since a few last decades, the concerns about prevention of the industrial pollutions have been increased[18]. The main areas of concern are waste air pollution and water pollution.

In the printing industry, there are three major types of wastes as the following:

1. Solid wastes : could consist of empty containers , used film packages , outdated material, damaged plates , developed film , expire dated materials , production tests, bad printing or spoilage , damaged products ,and scrap paper.

2. Water wastes: from printing operations contain lubricating oils , waste ink , cleanup solvents , photographic chemical acids , alkalis and plate coatings , as well as metals such as silver, iron, chromium, copper and barium.

3. Air emission: printing operations produce volatile organic compound (VOC) emissions from the use of cleaning solvents and inks, as well as alcohols or organic base and other wetting agents.

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[16] Francis Sanbach, Principles of pollution control, Longman, 1982, P.2.
[17] Finn R. Forsund & Steinar Strom, Environmental economics and management: pollution and natural, Croom Melm, London, 1988,PP. 18-19.
[18] Monteleone D M, environmental initiatives to aid flexographic printers 1997 ,flexo vol. 22,1,Jan 1997, PP.22-23.

The above mentioned residual wastes can be associated with the general process steps:

1. imaging,
2. prepress,
3. press including (the make -ready),
4. post press operations depending upon the degree of computerization and the type of printing press being used.

A wide variety of products and wastes are associated with each of these steps from waste paper and empty ink cans, to less visible wastes such as vapor emissions from inks and solvents, known as volatile organic compounds (VOCs) as shown in table 3.1.

Camera	Computer/ plate/cylinder	Make-ready	Press	Finishing/ bindery
Exposed waste film	Exposed waste film	Waste ink	Waste ink	Waste paper trimmings
Waste water	Waste water	Waste paper	Waste paper	
		VOCs	VOCs	VOCs
Spent (fixer-developer) silver	Spent (fixer-developer) silver	Empty ink container	Empty ink container	Waste glue-adhesive
Empty chemical containers	Damaged and unusable plates		Used plate-cylinder	
Proofs	Empty containers			

Table: 3.1: Residual wastes can be associated with the general process steps

Also after the post press may be released VOCs from the evaporation of the retention solvents in the printed products.

This chapter deals on the study of the pollution effect from printing inks on the environment in section 3.2. and the study of use water based inks to reduce this pollution effect from solvent based inks in section 3.3.

3.2.1 Occupational exposure through the printing ink manufacture

The printing ink manufacturing process consists of mixing and blend of all the powered pigments, binders, additives water and /or organic solvents in a batch process.
These processes may cause considerable emissions of volatile organic compounds (VOCs).

The exposure to raw pigment dust may occur if bags or drums are emptied into a mixture and depending upon the mixture is closed or open. Recently, it has been replaced by a closed system.
Exposures to solvents were higher in liquid than in past ink manufacturing. For examples, in liquid inks manufacturing the exposures to solvents were in job titles includes the mixer/weigher operated who operated the mixer for varnishes and ink, the pot washer

who cleaned mixing drums with solvent and the eigher who weighed ingredients[19].

On annual basis, the health and safety executive HSE in UK publishes guidance for occupational exposure limits[20] for some airborne substances including many solvent vapors and dusts, which are direct interest to the ink maker[21]. The tables (3.2), (3.3) show examples for these publish guidance. Similar guidances are published by many countries for example; the thresholds limit value[22] (TLV) in USA, and a maximum allowable concentration (MAK) in Germany.

	Long-term exposure		Short-term exposure	
	mg/m^3	ppm	mg/m^3	ppm
Ethylene glycol (vapor)	-	60	-	125
Isophorone	-	-	5	25
n-Butanol	-	-	50	150
Toluene	50	188	150	560
White spirit	100	575	125	720
n-Butyl acetate	150	710	200	950
Butan -2-one (MEK)	200	590	300	885
Methanol	200	260	250	310
n-Propanol	200	500	250	625
Ethanol	1000	1900	-	-

Table 3.2: Typical examples of recommended limits of ink raw material

	Long-term exposure		short-term exposure	
	ppm	mg/m^3	ppm	mg/m^3
Calcium carbonate (total)	-	10	-	-
Calcium carbonate (respireable)	-	5	-	-
Carbon black	-	3.5	-	-
Mica (total)	-	10	-	-
Mica (respireable)	-	1	-	-
Silica, amorphous (total)	-	6	-	-
Silica, amorphous (respireable)	-	3	-	-
Talc (total)	-	10	-	-
Talc (respireable)	-	1	-	-

Table 3.3: Specific dust limits which are set for some powder

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[19] Kay, K., Toxicologic and evaluation of chemicals used in graphic arts industries, clin.Toxicol., vol No 9, 1976.

[20] Health and safety executive, occupational exposure limits, guidance note EH40, 1993.

[21] R. H. Leach, R.J. Pierce, E. P .Hickman, M. J. Mackenzie and H. G. Smith, The printing ink manual, Blueprint, London, 1993, PP. 907-910.

[22] WHO, “printing processes and printing ink, carbon black and some nitro compounds” , IARC monographs on the evaluation of carcinogenic risk to human, vol. 65, Lyon 1996 PP. 53-55.

3.2.2 Printing inks as a source of environmental pollution

As mentioned in the introduction, it was increasing concern about the pollution and its effects on the environment. As a result of that, it leads to changes of many aspects of the way in which the materials and methods are used to manufacture the products that we use in our live. Such materials should be considered in the printing inks are[23]:

- Volatile organic compounds VOCs
- Pigments and additives containing heavy metals,

3.2.2.1 VOCs from the printing inks

The Volatile organic compounds VOCs constitute of abroad range of odorous and toxic substances include:

a) Hydrocarbons including:
  - olefins
  - aromatics

b) and various organic compounds including nitrogen oxides, sulfur and halogen

VOCs represent an everywhere problem in indoor and outdoor air pollution. They are emitted virtually from all industrial sources in one form or another in the atmosphere and they have harmful effects on plant and animal life, these effects ranged from a simple nuisance to a serious hazard.

The annual consumption of printing inks is over one billion kilograms; most of them are petroleum-based. A large amount of these inks are liquid inks used especially in flexographic and gravure.

These inks have highly volatile solvents (e.g. aliphatic and aromatic hydrocarbons, alcohol's, ketones, and esters) and rely on property for quick drying, because of their volatility; these inks give off VOCs to the air during printing. Other inks, such as inks, which were used in past years in lithography are not very volatile and release low amounts of hydrocarbons and alcohols to the air. The printer was obligated to ensure that:

1. all emissions were either free or essentially free from persistent solvent mist, droplets or fumed,
2. the concentration of the volatile organic compounds VOCs should not exceed as the following[24]:
   - 20 mg m^{-3} of organic compounds as those from uncompleted combustion including of H_2CO and comparable chemicals.
   - 100 mg m^{-3} for aromatic solvents
   - 150 mg m^{-3} for aliphatic and other solvents
   - 250 mg m^{-3} for alcohols from water-based inks

   Also, it is very important in the packaging printing to avoid the odorous pollutions, which is a special kind of air pollutant. Humans can perceive even extremely small

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[23] Ronald E Todd ,printing inks formulation principles, manufacture and quality control testing procedures, Pira , 1994, PP. 194-195.

[24] Ronald E Todd ,printing inks formulation principles, manufacture and quality control testing procedures, Pira , 1994, PP.89-99.

amounts of odorant, it is estimated that only 10^8 or 10^9 molecules of odorant vapor in nose is enough to trigger detection for example the 1 µg of ammonia in air constitutes approximately 10^{16} molecules, this mean 10^7 or 10^8 times more than the amount necessary for detection[25]. Most odorous substances are VOCs, without control of this pollutant may be affected on the package contents especially in the perception of aroma and taste of food packaged.

3.2.2.2 Heavy metal in the printing inks

The heavy metals can be defined as metals with a density greater than 3.5 - 5 g/cm^3. According to these definitions more than half of them about 90 natural chemical elements are heavy metals.

The noble metals silver, gold, and platinum are heavy metals. They include also, some non-metals or semi-metals like selenium and arsenic. Under this aspect, also some light metals (e.g. beryllium) would be "heavy metals".[26]

Sometimes this term "heavy metals" comprises elements which are regarded as (eco-) toxicologically critical (harmful to the environment and/or health), because the heavy metals tend to collect in organs such as the liver, thereby becoming a health hazard.[27] Heavy metals were present as pigments and additives in inks in the earlier times, today are banned from the inks.

3.2.3 Hazardous pollution effect on the printers from the printing inks

3.2.3.1 Healthy risks from VOCs from printing inks

All organic solvents, which are employed in inks and coatings, are toxicants for organisms in the concentrations on or into human skin they act to remove fat, they remove the protective layer and thus indirectly further the formation of skin redness, rashes and inflammation by enabling the external influence of atmospheric agents, chemical toxicants, bacteria or fungus[28].
Inhaled solvent vapors affect in differing ways the circulatory system, the nervous system, the lungs and the liver depending on the type of solvent[29,30]as the following:

a) Hepatic toxic agents: (e.g. carbon tetrachloride) affected in the liver
b) Nephrotoxic agents: (e.g. halogenated hydrocarbons) affected in the kidneys
c) Hematopoietic agents : (e.g. aniline toluidine; phenol) affected in the nervous system

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[25] Committee on Odors from stationary and mobile sources," Methods of controlling odors," in odors from stationary and mobile sources, National Academy of sciences, Washington, DC, 1979, Ch. 6, PP.179-242.
[26] Winnacker, Küchler: ChemischeTechnologie; Hanser, München.
[27] Charles Finley, Printing paper and ink, Delmar publisher, 1997, PP. 361-362.
[28] Thomas T. Shen, industrial pollution prevention, Springer -verlag, Berlin, 1995, PP. 41-42.
[29] Klaus Doeren & Werner Fretag & Dieter Stoye, water-borne coatings the environmentally frinendly alternative, Hanser verlag, 1994,P.15.
[30] T.Rawe, Stoffbelastungen in Flexodruckbetrieben,Wirtschaftsverlag NW, 2000, PP.13-17.

d) Anesthetic agents: (e.g. acetylene hydrocarbons, olefins, others alcohols) affected in the brain[31]

3.2.3.2 Health hazardous from heavy metals from printing inks

The following problems may be associated with heavy-metal absorption:

1. Cadmium is linked to damage kidneys, lungs and bones; it has been suggested that it causes coronary thrombosis, and has been linked to a brittle-bone disease[32].

2. Lead which has been associated with anemia[33], damage to the brain and peripheral nervous system, kidney damage, damage to the reproductive organs in men, and abortions and stillbirths in women.

3. Chromates are linked to skin ulceration and can cause allergic dermatitis. They are thought to increase susceptibility to skin cancer; inhalation of lead chromate pigment dusts is associated with a lung cancer in human being.

4. The occupational exposure to arsenic, primary by inhalation is causally associated with lung cancer[34]. It has been observed a clear exposure response relationships and high risks.

3.2.4 The present methods of reducing solvent emissions

As mentioned earlier, the biggest potential polluters are VOCs released from the drying system of the press, there are four basic[35] ways of reducing solvent emissions:

1. Recover the solvents for re-use is an interesting option if only one solvent is used in the ink formulation. Often however, a mixture of solvents is used that have different evaporation points, and therefore distillation would be expensive compared with the returns on solvent recovered. There are many ink manufactures in some parts of the world gaining increasing toward produce single-solvent inks to avoid this problem[36].

2. Use biological filters to destroy the solvents. This is only useful for concentration of solvent below 0.5 g / m^3. This means that, for general practical purposes, biological filters are not alternative.

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[31] Charles Finley, Printing paper and ink, Delmar publisher,1997, PP. 363.
[32] WHO, Cadmium environmental health criteria, vol. 134. Geneva , world health organization, 1992.
[33] WHO, lead environmental health criteria, vol. 165. Geneva , world health organization, 1995.
[34] WHO, arsenic and arsenic compound environmental health criteria , vol. 165. Geneva , world health organization, 2001.
[35] Anthony white , high quality flexography , Pira BPIF Publishing ,1992, PP. 75-77.
[36] Ronald E Todd ,printing inks formulation principles, manufacture and quality control testing procedures, Pira ,1994, PP. 9-10.

3. Thermal waste treatment is the strongest argument for pollution control[37]. Each of the other solutions has potential difficulties but must not be discounted completely, although this is frequently used. The cost and problem associated with atmospheric pollution and global warming cannot be ignored.

4. Use water-based inks to replace solvent-based ink products[38]. The use of this can be problematic because many presses are already set up for solvent ink drying. Press speed, image quality and drying techniques would all be compromised by attempting to get rid of water. But by using water based ink the solvent emissions to the plant air have been reduced by about 80%. The toxicity of the gaseous and liquid wastes has also been reduced by approximately 90 %. Hazardous liquid wastes have been eliminated.

For these reasons, water based inks are suggested as a solution to reduce the impact of the inks on the environment.

3.2.5 Waste ink disposal options

The printing ink wastes (either hazardous or non-hazardous) can be used in one alternative disposal way. Many gravure and flexographic inks are an energy sources that makes them useful as a supplement fuel source in cement kilns which destroy 99.9%[39] of the organic wastes. The metals component of the ink becomes chemically bonded with lime, clay, and other materials, thereby becoming part of the cement. These fuels are used as a 25-50% substitute for coal in high temperature kilns needed for the manufacture of cements[40].
Instead of this use in the cement industry some printers have invested in systems that recycle waste ink into usable ink. And others still send their waste inks to facilities that reformulate the ink [41].

3.3 Studying of the printing inks and environmental options

For the ink-formulation a variety of materials for a particular ink were used. Chosen substances into a given ink are dependent on many factors such as:

1. The printing process (lithography, flexography, gravure, silkscreen)
2. The type of printing press used
3. Printing speed being applied
4. The type of the substrates

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[37] Uberoi M; Zak K , Low temperature VOC oxidation catalysts, Flexo vol 22 No 5 may 1997 , pp 140-143.
[38] Moscuzza, S ,Environmentally friendly ink products, GATF world, Jun/feb 1996, P. 30.
[39] Charles Finley, Printing paper and ink, Delmar publisher,1997, P. 370.
[40] Coates Lorilleux, safety health environment, Puteaux Paris, 2001.
[41] Gary D. Miller & William J. Tancig, Ink and cleaner waste reduction evaluation for flexographic printers, WMRC, TR-12, Jan 1994.

As shown in Figure 3.1, the ink is composed of colorants (pigments/ dyes) and vehicle to carry them, because the pigments are finely ground solid particles -like chalk dust - they are worthless without a liquid to carry them to the surface to be printed and a binding substance to keep them there[42].

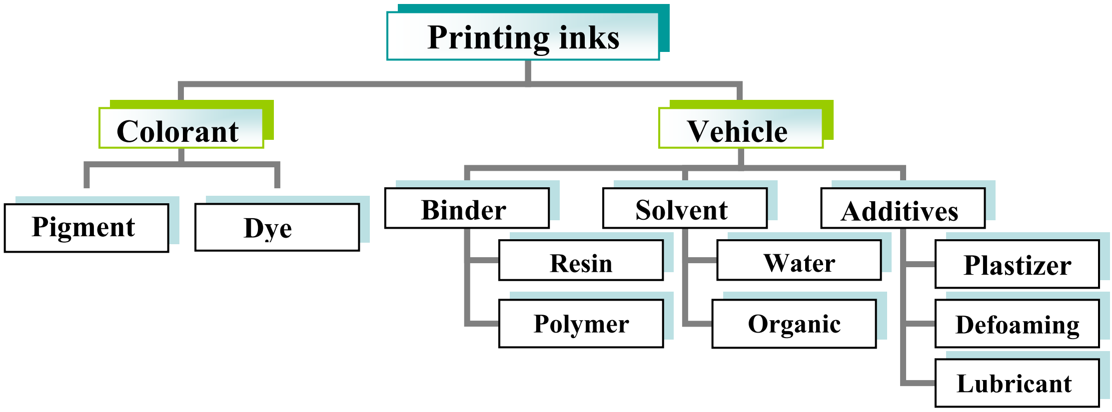

Figure 3.1: Illustration of the ink components

3.3.1 Ink Colorants

Pigments and dyes are obtained from both natural and synthetic sources and can be further subdivided into the chemical types: organic and inorganic.
The majority of these colorants used in inks are organic and of synthetic origin.

There are differences in properties between pigments and dyes, where the pigment is normally regarded as a colored compound that must be properly dispersed into a given vehicle system in order to develop its full color strength properties.
Dyes are used in printing inks because of their optical properties, e.g. transparency, high purity and color strength. The dyes must be dissolved into the vehicle system in order to develop this color strength, where the pigment is dispersed within the vehicle.

The great majority of printing inks contain pigments rather than dyes, a few contain mixtures of pigment besides dye and these are called semi- pigmented inks. The pigments have a good light fastness and good solvent and water resistance, while dyes show a rather poor light fastness and low solvent resistance. On the other side pigmented inks show unwished light scattering in transparent inks[43].

The pigments are the solid coloring matter in inks whether black and white or color, Pigments are also responsible for many of the specific properties of the inks, such as opacity, transparency and permanency to light, heat and chemicals.
The pigments usually determine whether or not a print will bleed in water, oil, alcohol, fat, acid or alkali.
Hence the pigments partially determine whether ink is suitable for a specific printing process or specific end use such as wrappers for butter, meat, or soap besides the

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[42] FFTA, Flexography principles and practices, flexographic technical association, Inc, 1992.
[43] Charles Finley, Printing paper and ink, Delmar publisher,1997.

acceptance of surface treatment such as varnishing, spirit varnished, lacquered, laminated, etc.
The pigments have a major effect in some ink properties such as ink viscosity and flow properties therefore, It must be careful chosen of the pigments to obtain an essential ink formulation[44].

3.3.2 Vehicle

The ink vehicle is the liquid portion of the ink; some printing inks are rather simplistic in the composition of their vehicles, while others are an amazingly complex collection of chemicals necessary to impart some desired characteristics to the ink.

The purpose of the vehicle in all inks is to carry the pigment to the substrate, hold it there and provide any desirable properties. So, the characteristics of the ink are depending on the vehicle composition, this composition will determine the following properties:

a. ink's stiffness
b. ink drying rate
c. ability to adhere to a particular substrate
d. degree of gloss
e. rub resistance
f. appropriateness to lithograph, gravure or any other printing process

Some references refer to vehicle as varnish, but abroad term sometimes supposed apportion of the vehicle that includes an ink's solvent, resin and /or drying oils but not excludes any drier or waxes.The term varnish also is used to refer to the clear coating that often applied on press to paper to affect the sheets gloss or protect the printed image, and do not refer to a portion of the ink[45].

3.3.3 Resin/ binders

As well as the ink pigments are solid particles that have to be carried to the substrate by a liquid vehicle, the ingredient needed to bind ink components one to another and therefore to the substrate is ink resin also known as the ink binder. Different types of resins are used to modify the physical and chemical properties of the printing ink on the printing press and on of the printed ink on the substrate. There are two basic classifications of resins:

3.3.3.1 Natural resins: major usage of it found in lithographic and letter press inks. It may be found in:

a. Casein protein as binder for decor printing inks
b. Pine trees, which are used in both pasty and liquid ink system
c. Celluloses resin which driven from cellulose fibers to provide binding and scratch and rub resistance to an ink's film

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[44] NAPIM, printing ink handbook ,USA, 1988, PP 16-20.
[45] Charles Finley , Printing paper and ink, Delmar publishers, 1997, PP.222.

d. Stylized rubber to improve excellent adhesion and rub resistance.

3.3.3.2 Synthetic resins, to impart particular characteristics to an ink or to be more compatible with other compounds in the ink, for examples:

a) Acrylic resins, to excellent adhere to most foils and packaging films in flexo, gravure, screen inks
b) Vinyl resins in screen inks
c) Maleics in lithographic and flexo inks
d) Polyamides in flexographic and gravure inks
e) Acrylics in flexographic, gravure and screen inks
f) Epoxies resin in offset metal decorating inks

Two or more of these used to be combined to capture the desired characteristics of each.

3.3.4 Solvents:

All ink resins are solid compounds that must be dissolved or nearly dissolved by the solvents before used in printing inks. The choice of solvent or diluents depends on many factors, such as the type of ink being manufactured (pasty or liquid), the substrate to be printed, and the type of the required drying mechanism. For example in flexo and gravure liquid ink formulation the choice of the solvent must achieve several considerations such as:

1. the solvent must be a liquid that dissolves the resin, but does not cause the pigments color to bleed.
2. it must evaporate at an acceptable rate.
3. it must be compatible with the printing plate material and must impart the flow and adhesion properties that are desired of the ink film.
4. the speed of the printing machine.
5. the substrate being printed.
6. any recycling or reclamation system in operation, possible environmental consideration.

A crucial factor in selecting the proper solvent is its volatility, the speed at which it evaporates to achieve the accurate drying time of ink film.

3.3.5 Additives:

Such as driers, waxes, lubricants, rheological agents, antioxidants, gums, starches and surface-active agents are used to impart special characteristics to inks.

3.4 Water based inks

The first relevant industrial use of water based printing ink took place in 1945s for pattern coating kraft linerboard for decorative corrugated cartons, the ink was based on casein and alpha protein which were inexpensive and had the right heat resistance for corrugated operations[46].

In the 1980s, the ink manufactures improved water-based inks complying with Clean Air Acts to reduce the pollution of the atmosphere with volatile organic components VOCs. And today, the water-based inks are successfully used in flexographic printing and gravure decor printing.

3.4.1 Advantages and disadvantages of water based inks

The printing with water-based inks has environmental advantages such as:

1. reducing the environmental impact during the printing process and later avoiding the release of retained solvent (VOC).
2. reducing potential for discharging toxic substances into a water system.
3. reducing the potential for fire explosion, thereby eliminating some of the costly provisions and regulations required for flammable solvents and inks.
4. reducing the amount of hazardous wastes
5. improving the working conditions in the plant therefore, reduce the health risk for the personal at the press and handling the prints through VOC emissions.
6. In the packaging printing it leads to avoid the negative effects in the perception of aroma and taste of the packaged goods through retained VOC.
7. brings the firms into compliance with almost every regulation.

In spite of all above advantages water- based inks still have some problems such as:

1) a longer time is required for the inks to dry, due to the higher latent heat of vaporization of water compared with many other solvents, for example it consumes $2{,}047 \times 10^6$ J to evaporate 1 kg of water; while it requires $7{,}744. \times 10^5$ J to evaporate 1 kg of ethanol. Therefore, more energy is required for drying water-based inks so that energy costs are increased[47].

2) as in the usual dryer the whole sheet (printing and non-printing areas) is heated, unprinted areas may over dry (on hygroscopic substrates) or may lose mechanical strength (on thermoplastic substrates) [48].

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[46] FFTA, Flexography principles and practices, flexographic technical association, Inc, 1992, P 540.
[47] NAPIM, printing ink handbook, USA, 1985,P. 39-41.
[48] Rodriguez, J.,& Saad A., Drying of water based inks with microwaves, IARIGAI 2004, Copenhagen.

3) slower absorption of water based inks into the substrate, as well as poor wetting properties on non-absorbent substrates, that is because the higher surface tension of water compared with other solvents for example:
   Water = 72.6 . 10^{-3} N/m at 20^0C; ethanol = 22.0 . 10^{-3} N/m at 20^0C.

4) the water of the ink leads to an unequal moisture distribution in hygroscopic substrates with unequal change of dimensions as consequence.

3.4.2 Composition of water based inks

The water based inks and coatings are based on binder as casein or on polymer emulsions or based on alkali-soluble polymers that form a film on drying. If the alkali-soluble polymer is made soluble with ammonia, it becomes insoluble when the ammonia evaporates.
Generally, the water-based inks are quite comparable in the composition to solvent-based inks; the typical ink formulation is like below[49] :

- Colorant (12 – 20 %)
- Vehicles (10 - 25 %)
- Solvents (1.0 - 5.0 %)
- Additives (1.0 – 7.0 %)
- And rest of contents constitute percentage is water.

The colorants may be pigments or dyestuffs, the vehicle consists of one or more resins dissolved in water and additives may be various modifiers such as waxes, antifoam agents, and slip or anti-slip agents.

3.4.3.1 Colorant in the water based inks

The colorants used in water inks are substantially the same as those used in solvent inks. The same basic dyes and pigments can be used, but there are several notable exceptions[50].

3.4.3.2 Vehicles in the water based inks

Two main types of the vehicles which are used in the water-based inks are the following:

- vehicles for reversible drying water-based inks

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[49] B.Leiheit, Stoffbelastungen beim Flexodruck, Bundessanstalt fürarbeitsshutz und Arbeitsmedizin, Projekt 1662, Dortmund , 1998, PP. 50-52.
[50] Cecilia Christiani,GFL&J.Anthony Bristow ; STFI, The drying mechanism of water-borne printing inks, TAGA's47th Annual technical conference, Orlando, Florida, April 1995.

- vehicles for irreversible (permanent) drying water-based inks

3.4.3.2.1 The reversible drying water-based inks

As achievement, VOC-free water based ink for example inks with casein as binder. Casein protein is recovered from skim milk by acid precipitation at a pH of about 4.5. Mineral acids can be used to promote precipitation, or the milk can be cultured with lactobacillus which converts milk sugar to lactic acid, with in turn precipitates the casein. In either case, the precipitated casein curd is washed free of acid, dried, and ground. Casein is frequently identified for method of its precipitation (i.e. "lactic casein")[51].
In order to improve the water resistance of the casein inks film after drying the ink film must be coated with water based lacquer. The laminating with a water-based lacquer is necessary because these inks do not dry permanently as consequently, having a low resistance to water or it solutions as shown in figure 3.2.
Such kind of inks used in the decor printing because of use of abound embedded laminating resin.

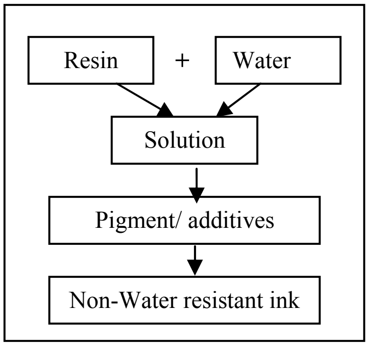

Figure 3.2: Water based inks reversible drying

3.4.3.2.2 The irreversible drying water-based inks

The vehicle used in irreversible drying water-based inks are substantially different from those in solvent- based inks, the greatest differences between both systems are the way in which resistance properties and re-solubility are controlled as shown in figures 3.3 and 3.4 . The vehicles for water-based inks are usually made from:

- Ammonia or amine- solubilized protein, casein, shellac, esterified formulated rosins, acrylic copolymers.
- Their mixtures.

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[51] Alan Lambuth,"Soybean, Blood, and casein glues" in Coating technology handbook, New York, Marcel Dekker, Inc, 1991, PP.465-466.

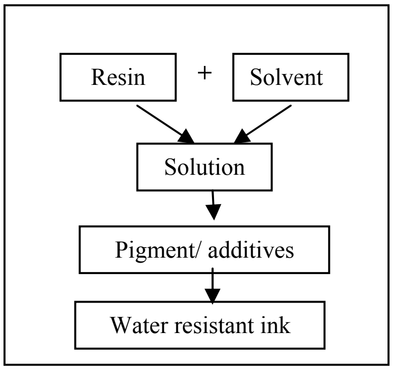

Figure 3.3: Solvent based inks

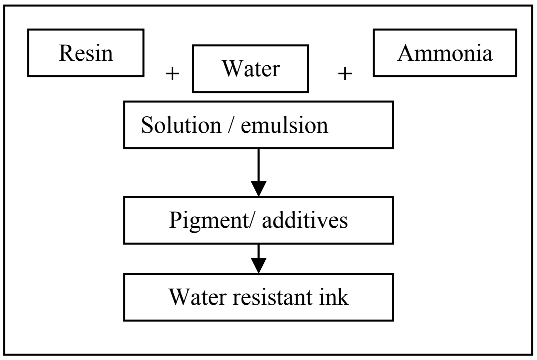

Figure 3.4: Water based inks irreversible drying

The acrylic polymers are the most successful of all water based ink technologies available, and the selection of these polymer systems is very important to achieve the balance between the resistance properties, and press performances of the water-based inks.
It can be classified into the categories of how they interact with the water in the following way:

1) Solution resins are molecules that have been dissolved by water to be a solution. This type enhances the ability of water to wet the pigment particles and help to make the ink film glossy but they don’t dry well.

2) Emulsion resins cannot dissolve in water but do forms an emulsion in water, this type have excellent drying properties, but have weak wet properties of the pigment and weak gloss.

Therefore, it must be used both types of resins (solution and emulsion) to obtain a good wetting of the pigment particles, drying quickly and a high gloss properties of the water based ink. Table 3.4 gives a comparison of both types of resins[52].

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[52] Roland A. Lombardi and James D. Gasper, “Acrylic polymers”, in Coating technology handbook, New York, Marcel Dekker, Inc, 1991, P.327.

Parameters	Solution resins (polymers)	Emulsion resins (polymers)
Particle size	.001 µm	0.1 µm
Molecular weight	low	high
Appearance	clear	opaque
Viscosity	high (depend mol. Wt.)	high (ind on mol. Wt.)
Solid content	low	high
Pigment dispersability	excellent	poor
Pigment stability	fair (depend on pigment)	good
Glass	high	low
Toughness	low	high
Printability	good	fair
Drying	slow	fast
Stability	good	depend on surfactant &emulsifier content
Easy of cleaning	good	fair
Water-resistance	fair	very good
Abrasion resistance	low	high
Heat resistance	low	high

Table 3.4: Comparison of aqueous soluble and dispersion resins (polymers)

3.4.3.3 Supplementary solvents in the water based inks

Three types of organic solvents- alcohols, glycol ethers and glycols- are used to improve solubility or change the viscosity of alkaline-soluble resins and control drying speed. The pigment is dispersed in aqueous phase. Co-solvents can be present in the resin phase in order to reduce the viscosity and softening point of the polymers[53].

3.4.3.4 Defoaming and antifoaming agents and additives

Because the vehicles of water based inks have a soapy nature they tend to foam. Subsequently they must be controlled with antifoaming agents or defoamers. These agents are water insoluble materials such as 2-ethyl hexanol, the overusing of these agents can cause high yield thixotropy plate swell, which cause casters or streaks. Waxes are used in water based inks to achieve slip and rub resistance.

3.4.4 The drying mechanism of the irreversible drying water-based ink

As well known, most prints demand an ink film that's insoluble in water for example a shopping bag must not bleed in rain. So the vehicle has to be soluble in water while being

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[53] Cecilia Christiani,GFL&J.Anthony Bristow ; STFI, The drying mechanism of water-borne printing inks, TAGA's47th Annual technical conference, Orlando, Florida, April 1995.

printed but must become insoluble after printing. To achieve that, alkaline solutions of acidic resins are used which are water-soluble salts similar to soap.
The soapy nature of this vehicle helps to wet disperse pigments in much the same way as soap wets and disperses soil. Therefore, the alkali-soluble vehicles are a good pigment wetter, display good rheology, and prevent drying of the ink in cylinders when the line is stopped during printing runs[54].

Acrylic resins are also used in inks and overprint varnish for both gloss and resolubility. In their acidic form, resins are insoluble in water, but once neutralized with amine or ammonia will accomplish both of resins and press resolubility for high quality printing. As shown in figure3.5. After printing on the substrate, the amine or ammonia evaporates[55] . As the result of this, the dried ink film becomes insoluble in water to be appropriate for most end uses[56].
Ammonia is the most common neutralizing agent due to its low cost and ease of evaporation as shown in table 3.5.

The pH matters because the degree of alkalinity affects the viscosity and printability of water based ink in much the same way that solvency or solvent balance affects the performance of solvent ink.
Controlling pH can be a problem with long runs of water based inks solubilized with ammonia or amines especially in hot weather[57].
Monoethylamine is used in many applications. Some times other amines are used, because they help improve resolubility. However, the amines are more expensive, require more energy to evaporate, and add to the VOC content.

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[54] G. Sen, A. m. Ink maker, 65-12 (1987).

[55] David D. Faux &Lloyd J.Rieber, printing technology, Delmar Publishers Inc, 3rd Edition, 365.

[56] Theodore G. Vernardakis , “pigment dispersion”, in Coating technology handbook, New York, Marcel Dekker, Inc, 1991, P.529.

[57] FTA & FFTAI, Flexography Principles and Practices, 4th Edition, USA, 1991, P.345.

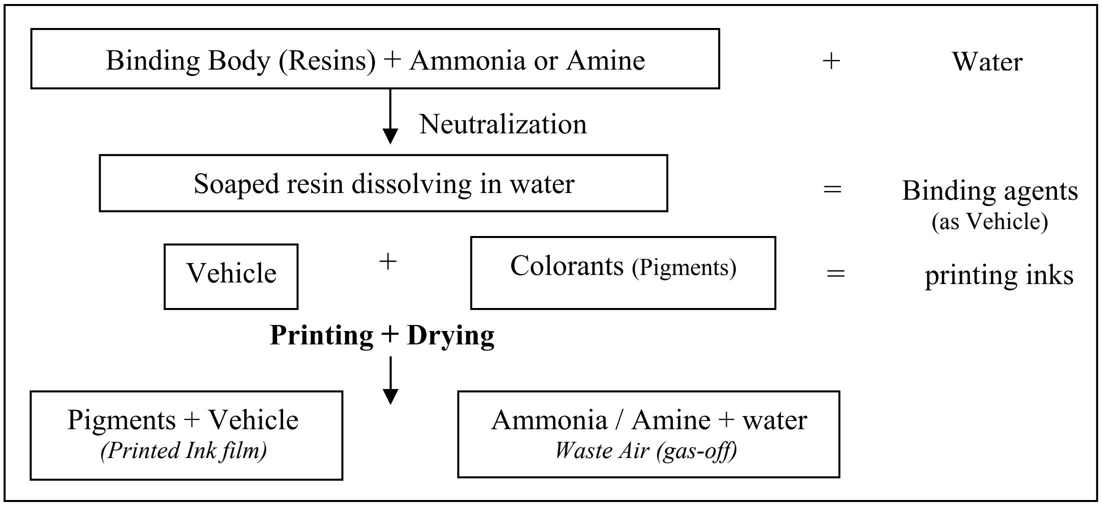

Fig 3.5: The mechanism of the drying water-based inks

Amine	Boiling Point (^{0}C)
Ammonia	- 33
Morpholine	128
Diethylaminoethanol	163
Monoethylamine (MEA)	170
Diethanolamine (DEA)	268
Triethanolamine (TEA)	335

Table 3.5: Boiling point of amine and amino group

Chapter 4

Fundamentals of Microwave Heating

Microwave is a portion of the electromagnetic spectrum with its frequencies in the order of GHz. The microwave is widely used in many industrial and military applications, such as in radar technology, communications and heating.

Microwave technique and many of its applications were developed during and just prior to World War II, where the most effort was concentrated on equipment for military use.

After World War II, the applications of microwaves outside military use were developed. One of these was microwave heating including industrial microwave processing systems as well as domestic and commercial microwave ovens.

Practically, two different frequency ranges can be distinguished in industrial processing:

- Radio frequencies (RF) below 100 MHz based on open circuits.
- Microwaves at frequencies above 500 MHz based on a waveguide to transfer the power to the material.

The international agreement designed the radio-frequencies 13.56, 27.12, and 40.68 MHz as well as the microwave frequencies is 915 and 2450 MHz.
The two most commonly used microwave frequencies are 915 MHz and 2.45 GHz. Usually, 915 MHz is found in industries and 2.45 GHz is for domestic use. In some countries, the frequencies might differ slightly. For example 896 rather than 915 MHz is used in the United Kingdom[58].

4.1 The Nature of Microwave

A part of the electromagnetic spectrum is shown in figure 4.1. It is obvious that the range of microwave frequencies is from 1 GHz to a few hundreds GHz, which is corresponding to wavelengths of 30 cm down to 1 mm.
For the electromagnetic radiation, the relation between the wavelength and frequency is given by:

$$\lambda = \frac{c}{f} \qquad (4\text{-}1)$$

where
c is the speed of light in free space (about 3.10^8 m/s)
λ is the wavelength in free space measured in meters.
f is the frequency (Hz).
Since microwave radiation is a part of electromagnetic spectrum so it is transverse waves in nature. Transverse waves means that it has electric and magnetic fields perpendicular

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[58] TseV.Chow Ting Chan & Howard C. Reader, Understanding microwave heating cavities, Artech House, USA, 2000, PP.10-11.

to each other and perpendicular to the direction of the wave propagation as shown in figure 4.2.

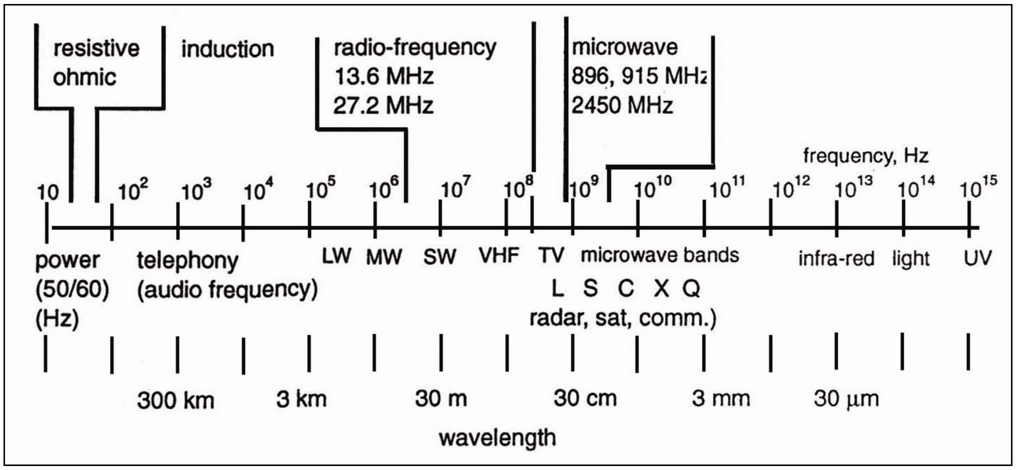

Figure 4.1: Microwave Spectrum, a part of the Electromagnetic Spectrum.

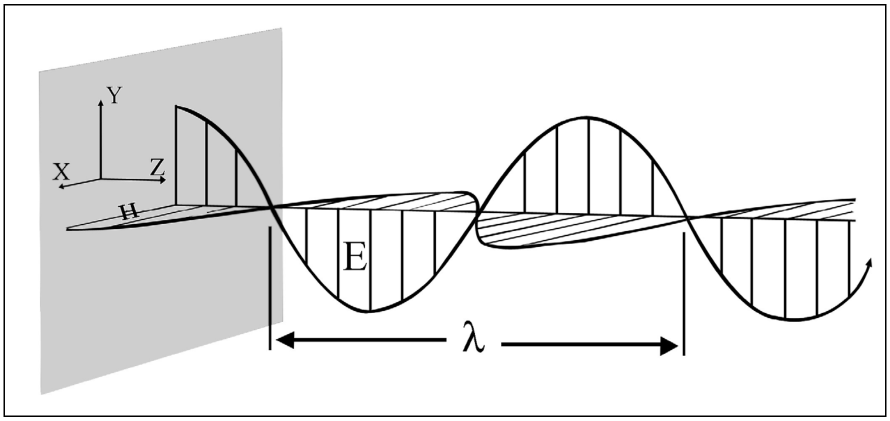

Figure 4.2: Electric and magnetic fields perpendicular to each other and perpendicular to the direction of wave propagation.

Microwaves are a non- ionizing as distinguished from ionizing radiation, they can interact with dielectric materials to generate heat by agitation of molecules in an alternating electromagnetic field. The microwave energy (in thermal applications) is transmitted through metallic hollow tubes called waveguides to avoid excessive radiation[59]. They are reflected by metallic objects, absorbed by some dielectric materials, and transmitted without significant absorption through other dielectric materials, as shown in figure 4.3. For example water, carbon and food with high water content are good microwave absorbers; glass, ceramics and most thermoplastic materials allow microwaves to pass with a little or no absorption.

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[59] H. Mooijweer, Microwave techniques, Philips technique library, 1971.

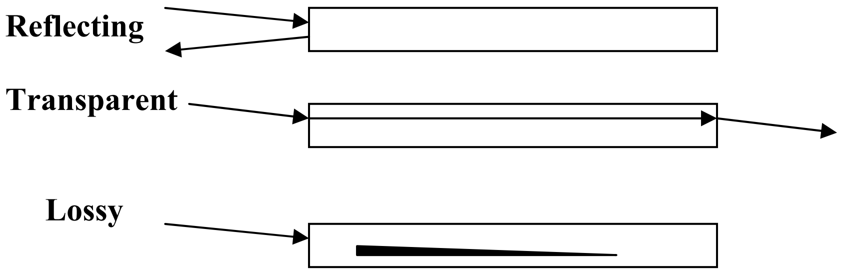

Figure 4.3: Reflection, transmission and absorption of microwaves when traveling from one dielectric material into another similar dielectric material.

4.2 Microwave heating systems

A microwave heating system in its basically form is constructed from:
- a microwave power source, it is usually a magnetron,
- an applicator, in our case it is a rectangular waveguide with slots for running the printed web through it,
- an isolator or circulator, which is placed between the microwave power source and the waveguide to protect the magnetron from damage caused by the reflected wave.

4.2.1 Magnetron

Magnetrons are devices which are efficient generators of microwave energy. The first constructed microwave power oscillator was a magnetron and it is still the most important microwave power generator for thermal applications.
The first magnetrons were developed prior to World War II in the late 1930 and early 1940s.There are two types of magnetrons[60]:

1. Pulsed magnetrons which have a very high peak output power from kilowatts up to several megawatts in a very short duration. The current frequency ranges of the pulsed magnetrons are ranged from less than1 GHz to over 5 GHz. These types of magnetrons are still used in radar applications.

2. Continuous wave (CW) magnetrons which have continuous output power from a few watts up to10 k watts, the most common application of this type is for use in the home microwave oven.

The magnetron is a cross-field vacuum tube; this means that the flow of electrons, the electric field and the magnetic field are mutually perpendicular to each other.

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[60] T.Koryu Ishii, Handbook of Mivrowave technology, vol. 2, Academic press, USA,1995, PP. 33-34.

The construction of a magnetron is as follows:

- A copper cylindrical high vacuum anode with an axial magnetic field from a permanent magnet or electromagnet. The inner surface of the anode is broken into equally spaced resonant cavities.
- Cathode or filament which is the source of electrons at the centre of the magnetron as shown in figure 4.4.

The operation of the magnetron can be summarized as follows:
Under the influence of electric and magnetic fields, the electrons generated from the heated cathode tend to move towards the anode in curved closed loop paths as shown in figure 4.5, thereby causing the resonant cavities oscillate. These oscillations interact with the electrons to release microwave energy at the desired frequency.
The microwave energy is coupled by means of a probe from one of the resonant cavities into an output coupling antenna, where it is launched into a hollow resonator waveguide, then the microwaves are propagating down the waveguide as sinusoidal wave[61].

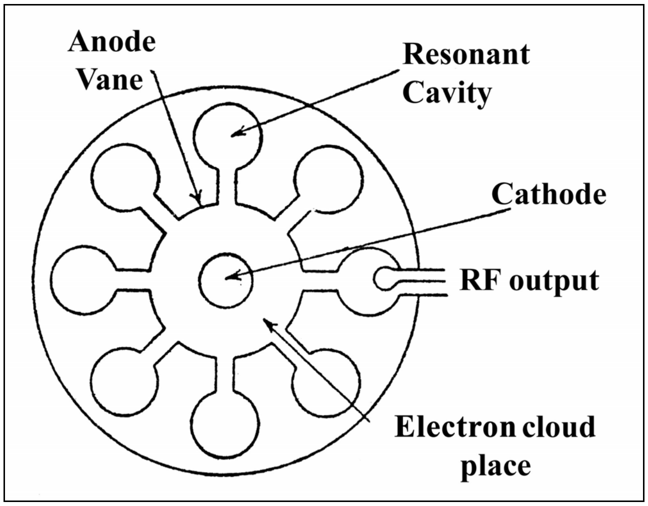

Figure 4.4: Essential components of the magnetron structure.

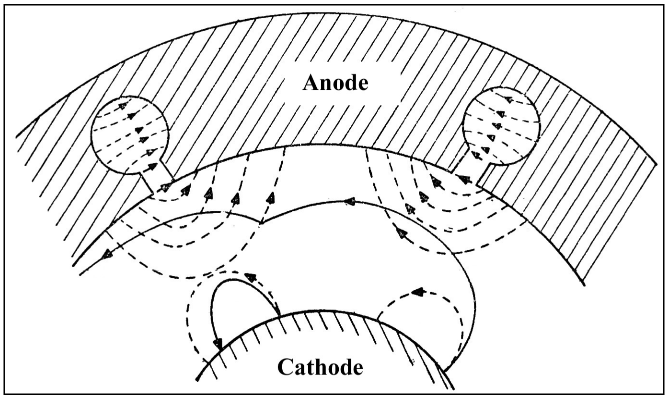

Figure 4.5: Electron space charge of an operating magnetron.

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[61] R.V. Decareau and R.A.Peterson, Microwave processes and Engineering, Ellis Horwood, UK ,1986 ,PP88-89.

The reflected microwave power can damage the magnetron because of impedance mismatching between the magnetron and the load. Therefore, an isolator or a circulator is used to minimize the reflected microwave power.

4.2.2 Circulator

The operation of the magnetron at higher than specified voltage standing wave ratio (VSWR) may result in unstable performance (moding) and possible damage to the magnetron, for this reason a circulator is used to match between the magnetron and the load.
The rate of the reflected power is characterized by the voltage standing wave ratio (VSWR), which can be defined as:

$$VSWR = E_{max} / E_{min} = (E_i + E_r) / (E_i - E_r) , \qquad (4\text{-}2)$$

where E_i and E_r are the incident and reflected electric field, respectively.
This means that the use of a circulator is necessary between the generator and load to reduce the power reflected back to the generator from the mismatched load and thus reduces the VSWR at the magnetron output.

The circulator is a three or four port device, which has the unique ability to couple energy between adjacent ports in one direction only, and isolate between non-adjacent ports, because the circulator has high attenuation in one direction and very little in the other.

Usually a three port circulator device is used; the paths of the transferred power to the load and the reflected power to the dummy load are shown in figure 4.6. It can be seen that the energy circulates around the device in only one direction. Port (1) is the input, port (2) is the output, and port (3) is terminated with a matched dummy load, which absorbs the energy reflected from the output port (2). A very small part of the energy is coupled from port (3) to the input port (1)[62].

As shown in figure 4.6, the implementation of the circulator is performed with one port connected to an external dummy load, where the reflected power is absorbed by the dummy load.

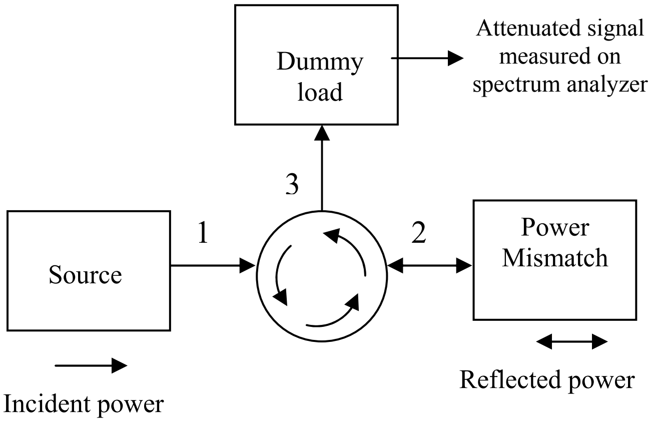

Figure 4.6: Three port Circulator (R.V.Decareau& R.A.Peterson)

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[62] R.V. Decareau and R.A.Peterson, Microwave processes and engineering, Ellis Horwood, UK, 1986,P71.

4.2.3 Waveguide applicator

There are several types of transmission lines which can be used according to their properties, e.g.:

1- Coaxial cables.
2- Hollow metal waveguides.
3- Dielectric waveguides.
4- Striplines.

In general, a waveguide consists of a hollow metallic tube of a rectangular or circular shape (cross section), which is used to guide an electromagnetic wave and by this to carry the microwave power. In waveguides the electric and magnetic fields are confined to the space within the guide walls. So no power is lost through radiation, and even the dielectric losses are negligible, since the guides are normally filled with air. However, there is some power loss by heat produced in the wall of the waveguides, but this loss is very small.

The waveguide acts as high-pass filter, in which only frequencies higher than a certain value known as cut-off frequency can be transmitted, the value of which is related to the physical dimensions of the waveguide.

In the most industrial microwave heating installations, the waveguides can be used as a device in which microwave energy interacts with the material being heated. In many cases, the heating chamber itself is based on waveguide technology; therefore a good applicator should assure an adequate conversion of the delivered microwave energy into thermal energy inside the load within the applicator[63].
In the next section, the basic parameters of waveguides and their characteristics will be discussed in details. These parameters are:

4.2.3.1 Waveguide materials

Materials commonly used in industrial microwave equipment should have high conductivity to minimize losses and easy to be manufactured. Most industrial equipments use aluminum waveguides for high power transmission, because it has the following properties:

- low attenuation
- high electrical and thermal conductivity
- relatively low-cost with an upper limit
- it can be used without forced cooling up to 100 kW at 900 MHz and 30 kW at 2450 MHz.

Copper and brass are usually confined to laboratory equipment at 2450 MHz.
Stainless steel should not be used for power transmission because it has a low electrical and thermal conductivity[64].

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[63] Harry E. Thomas, Handbook of microwave techniques and equipment, Prentice-Hall, London, 1972, P. 49.

[64] Roger Meredith, Engineers' Handbook of industrial Microwave Heating, IEE, UK, 1998, P.123.

4.2.3.2 Waveguide size

Waveguide sizes have been standardized for the different frequency bands in the microwave spectrum. Usually the sizes of waveguides are chosen depending on:

- the operating frequency.
- the mode.
- the amount of attenuation that can be tolerated.

The frequency range in the waveguide determines the *a* dimension, and the *b* dimension determines the limit due to voltage breakdown, consequently determines the maximum capacity of the power, which can be handled.

Practically, the *b* dimension is choose about half of *a* dimension as in Figure (4.7) shown. The wall thickness should not be less than 1.5 mm at 2450 MHz to give reasonable resistance against damage from impact.

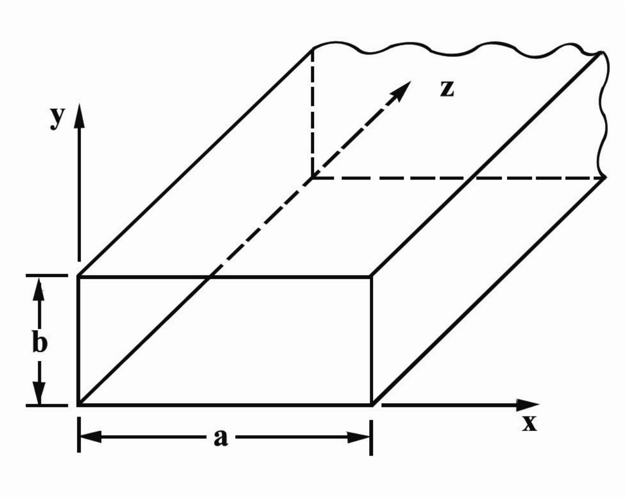

Figure 4.7: Rectangular waveguide with aspect ratio (a = 2b).

If a rectangular waveguide transmits only a wave of that frequency for which the waveguide shows an optimal behavior (dominate mode), then the wide *a* dimension must not be greater than the free space wavelength λ_0 and the narrow *b* dimension should not exceed one half the free space wavelength λ_0, this means that the cross-sectional dimensions of a rectangular guide should lie in the ranges[65]:

$$0 \langle \ b \ \langle \frac{\lambda_0}{2} \qquad (4\text{-}3)$$

$$\lambda_0 \rangle \ a \ \rangle \frac{\lambda_0}{2} \qquad (4\text{ -}4)$$

These waveguide sizes are available commercially from many manufacturers[66] as shows in the following table 4.1:

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[65] Harry E. Thomas, Handbook of microwave techniques and equipment, Prentice-Hall,London, 1972,P. 60.

[66] Roger Meredith, Engineers' Handbook of industrial Microwave Heating, IEE, UK, 1998, P.124.

Microwave frequency MHz	**Waveguide designation**	**Internal dimension (m)**	**TE_{10}mode (λ_c m) cut-off frequency (f_c) MHz**
896±5%	WG4;RG204U; WR 975	0.248×0.124	0.496 (604 MHz)
915±5%	WG4;RG204U; WR975	0.248×0.124	0.496 (604 MHz)
2450±5%	WG9A;RG112U; WR340	0.0864×0.0432	0.1728 (1735 MHz)

Table 4.1: The commonly used sizes of the waveguides

4.2.3.3 The main mode in rectangular waveguides

Each of the possible field configurations in waveguides is called a mode.
Actually, an infinite number of modes or wave configurations can exist in a waveguide; in lossless waveguides, the modes may be classified as:

- Transverse Electric mode (TE).
- Transverse Magnetic mode (TM)

Each mode of the waveguide will only propagate above a certain frequency, because it has a minimum frequency below which the energy will not propagate, this frequency is called the cut-off frequency of the mode.

Usually TE_{mn} and TM_{mn} symbols are used to describe TE and TM modes. The subscript *m* indicates the number of half wave variations of the electric field along the *a* dimension of the waveguide, and *n* indicates the number of half wave variations of the electric or magnetic field along the *b* dimension of the waveguide.

The mode with the lowest cut-off frequency in a particular waveguide is called the dominant mode, this dominant mode in a rectangular waveguides with $a > b$ is the $TE_{1\,0}$ mode as shown in Figure 4.8. The dominant mode

- is a very simple mode with respect to the field patterns, [67]
- has the longest operating wavelength and
- has the lowest frequency which will propagate in the waveguide.

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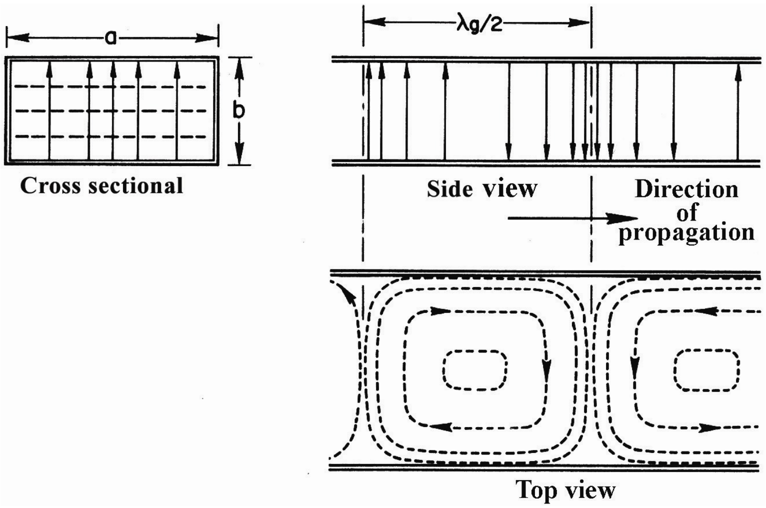
[67] Ashim K. Datta & Ramaswamy C. Anantheswaran, Handbook of microwave technology for food applications, Marcel Dekker, Inc, New York, 2001, PP. 14-15.



In the TE $_{10}$ the first subscript denotes that there is one complete half-wave pattern across the "*a*" dimension , the second subscript denotes that there is a constant field strength across the "*b*" dimension.

Figure 4.8: Fields of the dominant TE $_{1\,0}$ mode in a rectangular waveguide

As the normal mode TE $_{1\,0}$ propagates inside the waveguide the electric field only acts in *y* direction and the magnetic field acts in the *x-z* plane. The electric field consists of straight lines parallel to the y-axis while the magnetic field consists of closed loops in the x-z plane as shown in figure 4.9, also the whole field patterns appear to be moving in the z-direction with a speed as follows[68]:

$$v_p = f\,\lambda_g \qquad (4\text{-}5)$$

where v_p is the phase velocity

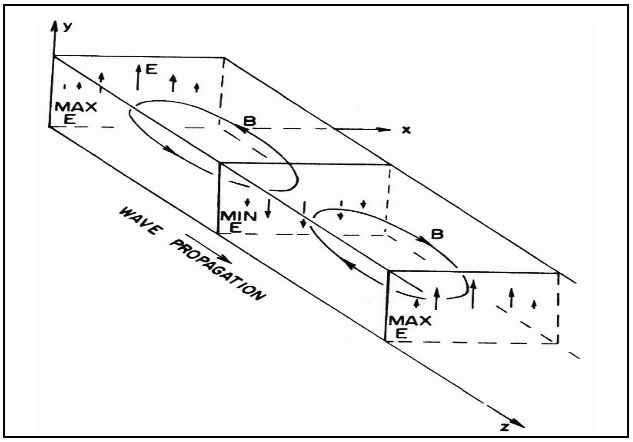


Figure 4.9: The z- dependence of the field in the waveguide.

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[68] A J Baden Fuller, Microwaves An introduction to microwave theory and techniques, Pergamon Press UK, 1990, P.107.

4.2.3.4 Cut-off and waveguide wavelength

The wavelength in the direction of the propagation along the waveguide is the waveguide wavelength (λ_g), and it is different from the free-space wavelength (λ_0). λ_g can be calculated by the equation:

$$\lambda_g = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2}} \quad , \tag{4-6}$$

where:

λ_0 is the free-space wavelength,
λ_c is the cut-off wavelength.
The value of the cut-off wavelength for any TE or TM mode in the waveguide is as follows:

$$\lambda_c = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}} \tag{4-7}$$

Therefore the cut-off wavelength for the TE_{10} mode obtained by m =1 and n = 0 in the above equation is as follows:

$$\lambda_c = 2a \tag{4-8}$$

The waveguide wavelength is significant because the equipment components as the waveguide, the magnetron, and some extent-heating chamber will be determined by the waveguide wavelength values. And the cut-off frequency is significant because for lower frequencies the electromagnetic energy cannot travel down the waveguide.

4.2.3.5 Attenuation in the waveguide

As electromagnetic waves travel down the waveguide, currents are induced in the walls. These lead ohmic losses and the wave is therefore gradually attenuated as it travels.
As consequence, the attenuation in waveguide is a function of the[69]

- waveguide material and dimension,
- the wavelength and
- the mode of propagation.

Attenuation varies with frequency and, when the frequency is approaching the cut-off frequency then attenuation increases rapidly. This means that, if the frequency of the excited mode is above the cut-off frequency (f_c), then electromagnetic energy will transmitte down the waveguide with little attenuation. If the frequency is below the cut-off frequency then a very high attenuation occures even on a short distance.[70]

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[69] Kc Gupta, Microwaves, Wiley Eastern Limited, 1979, P.21.

[70] TseV.Chow Ting Chan & Howard C. Reader, Understanding microwave heating cavities, Artech House, USA, 2000, P.24.

To minimize the ohmic losses, the waveguide wall resistance is made as low as possible. For the $TE_{1\,0}$ mode in the rectangular waveguide, the equation for the attenuation is given by[71]:

$$\alpha = R\sqrt{\frac{\varepsilon_0}{\mu_0}}\left[\frac{1+\frac{2b}{a}\left(\frac{\lambda_0}{2a}\right)^2}{\sqrt{\left\{1-\left(\frac{\lambda_0}{2a}\right)^2\right\}}}\right] \quad \text{nepers per meter} \qquad (4\text{-}9)$$

where α is the attenuation in nepers per meter, R is the surface resistance.

The electric field strength decays exponentially depending on the attenuation value as follows:

$$E = E_{max}e^{-\alpha z} \qquad (4\text{-}10)$$

4.2.3.6 Penetration depth

If a uniform plane wave is impinging on a plane lossy half space, then the field intensity and its associated power flux density fall exponentially with distance from the surface, because the power absorbed in an elemental volume of the material is proportional to the power flux density flowing through it. By this, the power dissipation falls exponentially from the surface, too.

This means, when the plane waves are incident on a thick lossy dielectric material, then the energy level drops exponentially according to[72]:

$$P = P_0\, e^{\frac{-2d}{\delta_p}} \qquad (4\text{-}11)$$

where P_0 is the rate of heat generation at the surface, d is the distance into the material from the surface and δ_p is the power penetration depth and related to the properties of dielectric materials with small losses according to[73].

$$\delta_p \approx \frac{1}{2}\left[\frac{\lambda_0 \quad \sqrt{\varepsilon'}}{2\ \pi\ \ \varepsilon''}\right]. \qquad (4\text{-}11\text{ a})$$

Therefore the penetration depth is defined as the distance from the surface of the dielectric material at which the amplitude of the incident wave drops to 1/e (about 37%). The penetration depth of microwaves energy is much larger than the thickness of the printed web with water based ink film.

4.2.3.7 Slots of waveguides and wall currents

In some microwave applications, the material is required to lie in the maximum of the electric field inside the waveguide to couple effectively with the flowing microwave energy.

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[71] A.C. Metaxas & R.J. Meredith, Industrial microwave heating, Peter Peregrinus Ltd, UK, 1983, P.123.

[72] Ashim K. Datta & Ramaswamy C. Anantheswaran, Handbook of microwave technology for food applications, Marcel Dekker, Inc, New York, 2001, PP.120-121.

[73] David Jiles, Introduction to the electronic properties of materials, Nelson thornes, P .187, 2001

To achieve that, the waveguide should be slotted at the centre of its two broad faces (walls).

In the waveguide, the fields are supported by electric currents on the internal side of the waveguide walls. If the waveguide is operated in the dominant TE $_{10}$ mode, then the wall currents at the centre of the broad faces are purely longitudinal, so that a longitudinal thin slot in the centre of these faces does not interrupt the current path, and negligible microwave energy lacks from a slot[74].

There are different types of slots that can be cut through the waveguide faces as shown in figure 4.10 such as:

1- Longitudinal slots (non-radiating slots) which are located in the centre of the broad walls of the waveguide. This means that the longer dimension of these slots run parallel to a current line. These slotes cause only minor perturbation in the current distribution and litte energy is radiated out into space[75]. Therefore these slots are perfectly located in order to keep the current and energy inside the waveguide.
2- Transverse slots (radiating slots) which cut current lines, therefore a significant amount of energy is radiated.

Thus, the knowledge of the current patterns is important as it enables slots to be correctly positioned in the walls to serve various purposes. In this manner, the non- radiating slot was made in a rectangular waveguide operated in the dominant mode TE $_{10}$ in the middle of the broad faces.

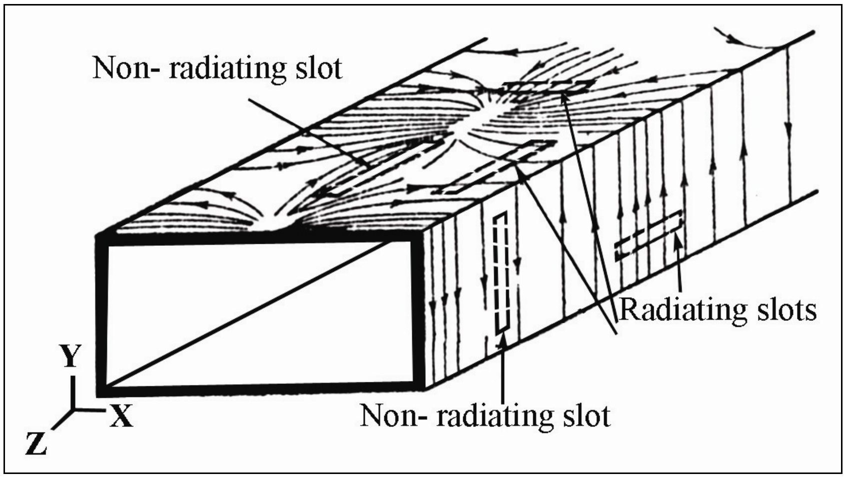

Figure 4.10: The location of the slot and the direction of the wall currents in waveguide in a TE $_{10}$ mode.

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[74] A.C.Metaxas & R.J.Meredith, Industrial microwave heating, Peter Peregrinus Ltd, UK, 1983, P.116.

[75] TseV.Chow Ting Chan & Howard C. Reader, Understanding microwave heating cavities, Artech House, USA, 2000, PP. 225- 227.

4.3 Interaction between materials containing water and microwave fields

The efficiency of the evaporation of the moisture of wet printed ink films by heat produced by high frequency fields depends on the dielectric properties of the water in the printed ink film and the printed substrate. These properties vary not only with the frequency and the field orientation, but also with the moisture content, temperature, and printed ink film viscosity. Considering these parameters and the specific heat of the substrate, estimation of the power absorption can be made.

In the next sections some concepts for the interaction of paper and water as the solvent in water-based inks with microwave frequency will be briefly studied.

4.3.1 Microwave heating mechanisms:

Only materials capable to absorbing microwave energy are heated by microwaves, these materials are generally classified as lossy dielectrics[76].

The conversion of microwave energy into heat involves the interaction between microwave fields and the conductivity or the dielectric properties of the material.

The most important mechanisms by which microwaves produce heat within liquids and solids are:

- Dipole rotation.
- Ionic polarization.

4.3.1.1 Dipole rotation (orientation polarization):

The water molecules have a form of a symmetrical triangle with the angle between the two O-H bonds being about 105 degrees. The electrons associated with the hydrogen atom shift towards the oxygen atom as a result of the strong attraction from eight positively charged protons in the nucleus of the oxygen atom[77]. This shift leaves the oxygen end of the molecule negative and the hydrogen end positive thus constituting an electric dipole, therefore these molecules are called polar molecules[78] as shown in figure 4.11.

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[76] Kingston, H.M & L.B.Jassie, Introduction to microwave sample preparation: theory and practice, American chemical society, Washington , 1988

[77] Suparna Mitra, the potentional of Microwave Heating for sludge dewatering and drying ,USA, 1990

[78] Richard P. Feynman &Robert B. Leighton & Matthew Sands, The Feynman lectures on Physics Mainly electromagnetism and matter, Vol.II , 7th , 1972, PP.11-1.

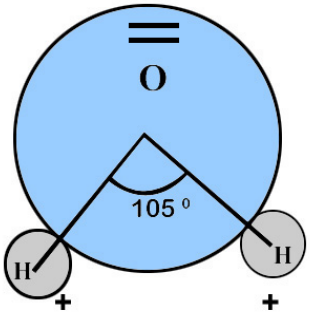

Figure 4.11: The atoms are not arranged (bonded) linearly (H-O-H) but bent at an angle of about 105°

The dipole rotation heating mechanism depends on the existence of polar molecules as the water molecules in the ink film.

Under normal conditions (in the absence of an electric field), the polar molecules (dipoles) are randomly oriented. In presence of an electric field, the polar molecules line up with the field. As an alternating field is applied, the polarity of the field is varied at the rate of the microwave frequency and the molecules attempt to align themselves with the changing field. Heat is generated as a result of the rotation of the molecules. When the field is removed, the molecules return to their random orientation.

This means that this alignment and realignment in response to an alternating electric field causes rapid oscillation of the dipoles which generates heat as a result of molecules friction with other molecules as shown in figure 4.12.

The rate of oscillation is varied at the rate of the microwave frequency. Also the molecules attempt to align themselves with the changing field and the relaxation time of dipoles. The orientation polarization is the most significant in the microwave heating application above 1 GHz.

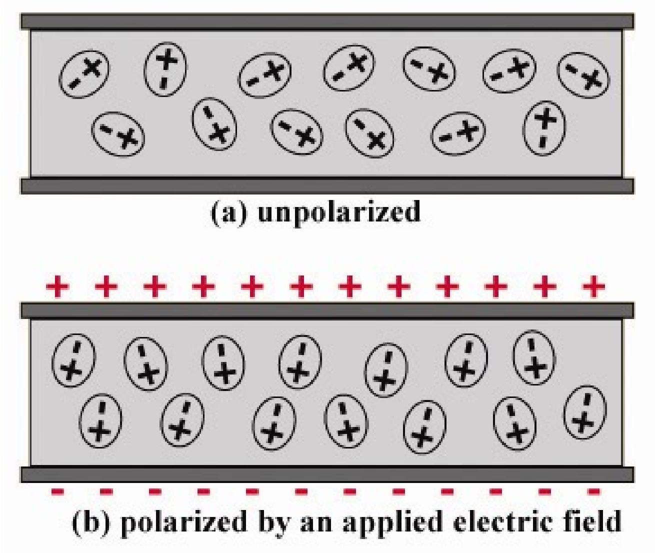

Figure 4.12: Dipole rotation due to changing field

4.3.1.2 Ionic polarization

Ionic polarization occurs when ions in solutions move in response to an electric field. Ions carry an electric charge and are accelerated by the electric field. Kinetic energy is given up by the field to the ions, which collide with other ions, converting kinetic energy into heat.

With increasing concentration and density of the solution more collisions occur, and more kinetic energy is released.
The generation of the heat is recognizable as an increase in the temperature of the dielectric material[79]. The Ionic polarization mechanism is less important than the dipole rotation.

4.3.1.3 Dependency of the heat generation as function of frequency and electric field

The water and the ions are the primary components of water based inks that absorb the microwaves leading to volumetric heating. The volumetric heating rate or the power dissipated of the microwaves is related to the electric field strength E is

$$\frac{P}{V} = 2\pi f \varepsilon_0 \varepsilon'' E^2 \quad , \qquad (\mathrm{W/m^3}) \qquad (4\text{-}12)$$

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[79] R.V. Decareau and R. A. Peterson, Microwave processes and Engineering, Ellis Horwood, UK,1986, PP. 41.

where

- f is the frequency of microwaves.
- ε_0 is the permittivity of free space.
- ε'' is the dielectric loss of the material.
- E is the value of the electric field.

4.3.2 Dielectric properties

The Dielectric properties describe how materials interact with electromagnetic radiation. The materials interact only with the electric part of the electromagnetic field[80]. Dielectric material is characterized by the real and imaginary parts of the complex permittivity as on formula[81]:

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (4\text{-}13)$$

where

- ε'' is the relative loss factor, which is the imaginary part of the complex permittivity and which indicates how well a material absorbs energy from the electric field passing through it and how much energy is converted to heat.
  lossy material with a high ε'' therefore will absorb energy well and heat quickly, on the other hand , materials with low ε'' are transparent. Therefore all material with an ε'' between ($10^{-2} < \varepsilon'' < 3$ are suitable for dielectric heating
- ε' : is the relative dielectric constant for the material which is used as a measure for the microwave energy density in the material .
  Both parts of the complex permittivity are frequency and temperature dependent[82].
  In addition, the relation between both parts ε'' and ε' are given by the following equation[83]:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \quad , \qquad (4\text{-}14)$$

where **tan δ** is called the loss tangent and expresses the share of the dielectric losses. The dielectric properties vary with frequency and temperature.
Moreover, the dielectric properties of composite material such as inks depend on its moisture and how many ions are present[84]. Therefore, the absorption of electromagnetic energy in pure water or in presence of ions depend on the frequency.

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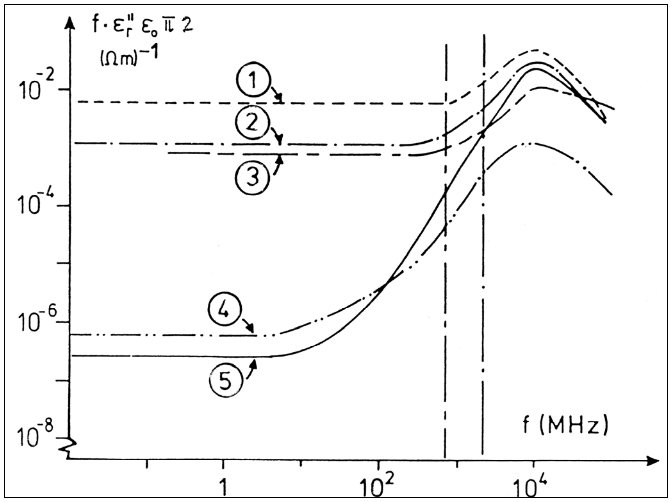
[80] Camelia Gabriel and others, Dielectric parameters relevant to microwave dielectric heating, Chemical society Reviews, vol No 27, 1998.

[81] Stephen F. Adam, Microwave theory and applications, Hewlett Packard, ,Englewood Cliffs, New Jersey, 1969, PP.19-20.

[82] Von Hippel, A.R., dielectrics and waves. Wiley, new York, 1959

[83] A J Baden Fuller, Microwaves, An introduction to microwave theory and techniques, Pergamon Press, UK, 1990, P. 67.

As shown in figure (4.13) [85] pure water owns low losses in the frequency rang below about 100 MHz followed by a strong increase of losses for the higher frequencies up to the so called relaxation frequency at about 22 GHz. However, solutions show much higher losses also for low frequencies if ions are present, with small a rise due to the relaxation[86]. The reason for the relaxation effect is that for frequencies above the relaxation frequency the dipoles cannot follow any longer the oscillating electrical field, therefore ε` drops from the high values to rather small one, while the losses own a maximum at the relaxation frequency.



1) 0.5 molar NaCl solution (25 ^{0}C),
2) 0.1 molar NaCl solution (25 ^{0}C),
3) Meat (25 ^{0}C),
4) pure water (95 ^{0}C),
5) pure water (25 ^{0}C)

Fig 4.13: The absorption of microwave energy as function of frequency

The corresponding relaxation time is given by the Debeye[87] equation (4-15):

$$Z = \frac{4\,\pi\,\eta_v\,a^3}{k_b\,T} \qquad (4\text{-}15)$$

where:

Z : The relaxation time
η_v : The viscosity of the ink film
a : Radius of the rotating dipole
k_b : Boltzmann constant (1.38 x 10^{-16} erg/grad)
T : Absolute temperature

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[84] Mudgett, R.E., Microwave properties and heating characteristics of food, food technology. Vol 40 (6): 84-93.1986.

[85] Günter Nimtz, Mikrowellen Einführung in Theorie und anwendung, Wissenschatsverlag, Zürich, 1990, PP.169-171.

[86] Ernest C. Okress, Microwave Power engineering, volume 2, Academic Press, New York, 1968, PP.208-209.

[87] Josef Gefahrt, Hochfrequenz- Erhitzung in Holz, Helmut Bücking Verlag Prien/ Chimsee 1962, P. 33.

Obviously, the relaxation time (Z) is a function of temperature and viscosity. It is the time interval characterizing the restoration of a disturbed system to its equilibrium configuration after a microwave field has been applied.
The behavior of (Z) varies widely in liquids and in solids. i.e. for water at room temperature, (Z) is about 5×10^{-11} s, the consequence is the maximum value of $2 \pi f\ \varepsilon_0\varepsilon''$ at about 20GHz in figure 4.13**.**

4.3.2.1 Dielectric properties of paper

Generally, the dielectric constant or permittivity of any material is a measure of the ability to polarize its constituents. Cellulosic materials such as paper contain space charges and permanent polar groups.

The value of the dielectric constant increases linearly with the amount of the water content. As shown in figure 4.14(a), the dielectric constant (ε`) is a function of the moisture content. Figure 4.14(b) shows the loss factor (ε``) as a function of moisture content, too. It can be seen that there are only small differences between the value of ε' and a differences in variation of paper and board with moisture content at microwave 2.45 GHz and radio 27.12 MHz frequencies.

In addition, the dominant loss mechanism at 2.45 GHz is probably dipolar re-orientation whereas at low frequency 27.12 MHz conduction loss is the important mechanism at high moisture content[88]

For paper, the critical moisture content is estimated to be about 3-6%, respectively. Below this critical value water has essentially no effect and polar groups are unable to contribute significantly because of the strict hindrances due to hydrogen bonding. At moisture above this critical value the polar groups are more labile and dielectric dispersion was observed[89].
From figure 4.15 may be inferred that also for paper with a moisture up to 5% an increase of the temperature will tend to increase the loss factor of paper.

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[88] A.C.Metaxas and J.L.Driscoll, A comparison of dielectric properties of paper and board at microwave and radio frequencies, journal of microwave power. 9(2), 1974.

[89] Richard E. Mark & Koji Murakami, Handbook of physical and mechanical testing of paper and paperboard, volume 2, Marcel Dekker, INC, New York, 1984, PP. 172-190.

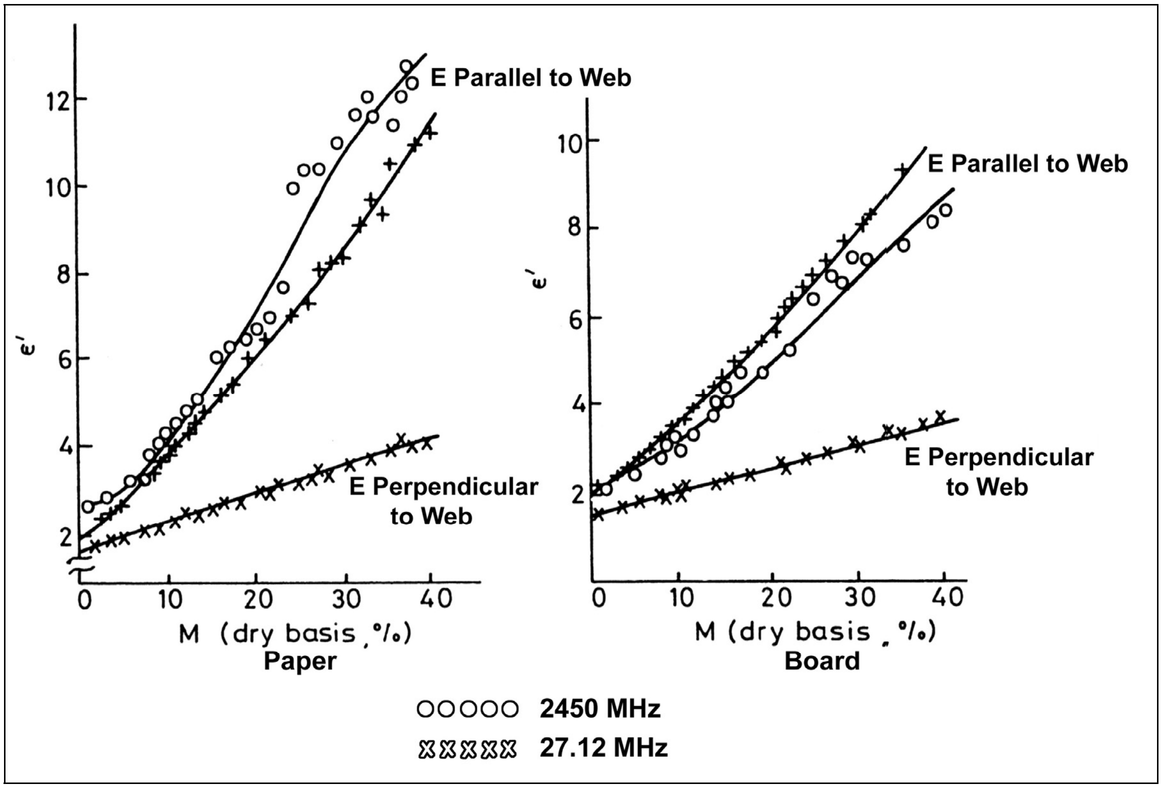

Figure 4.14 (a): Dielectric constant of paper and board as a function of moisture content for two frequencies and field orientations

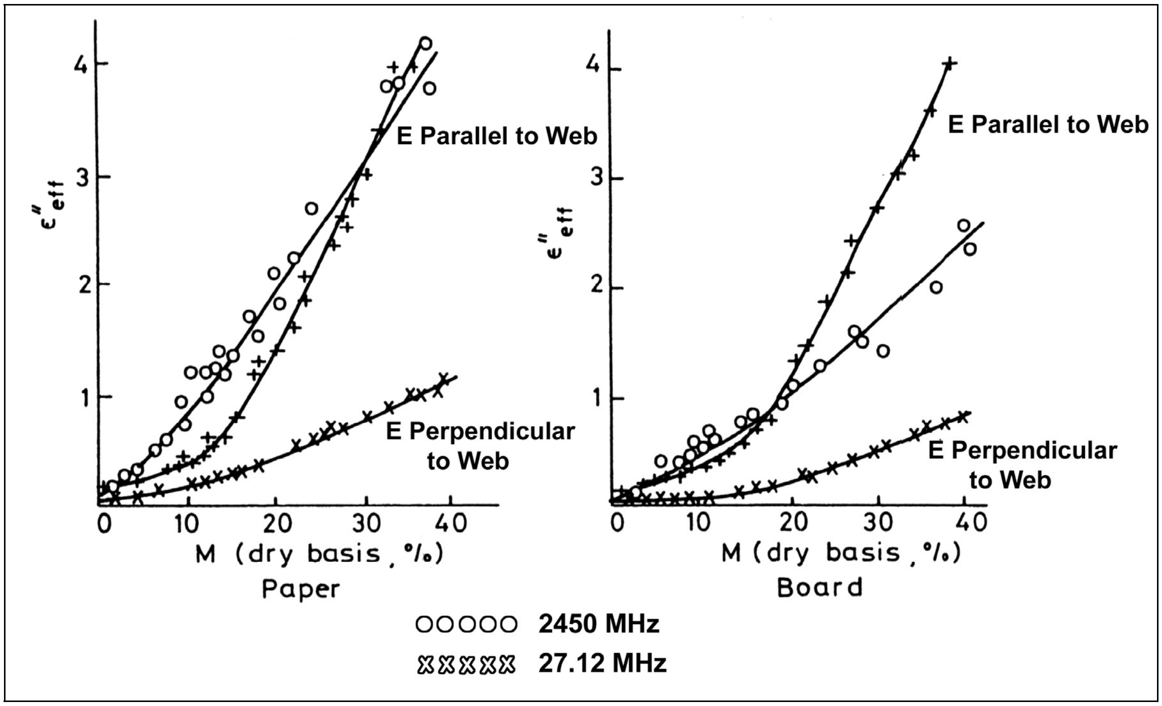

Figure 4.14 (b): Loss factor of paper and board as a function of moisture content for two frequencies and field orientations

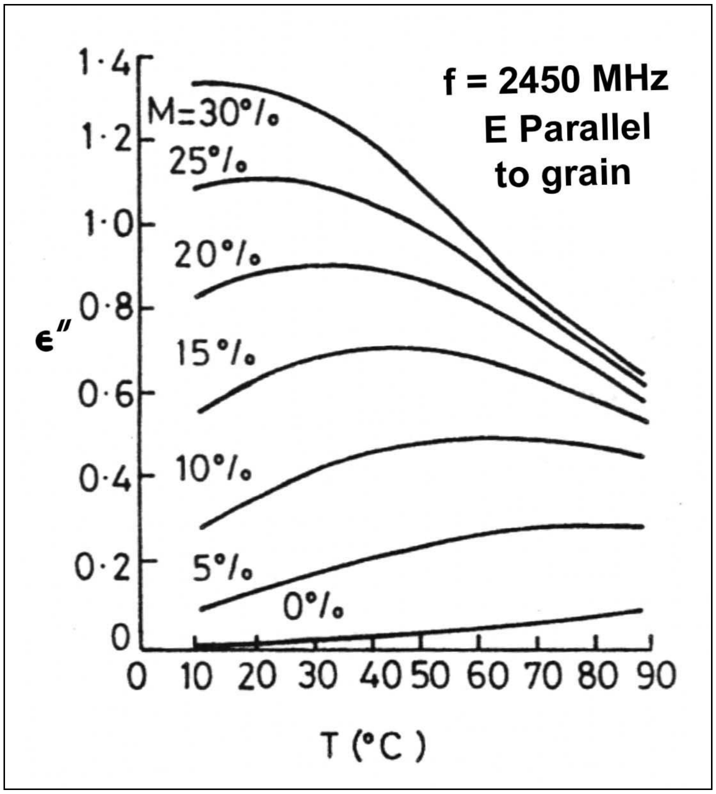

Figure 4.15: The relation between loss factor and temperature of wood

4.3.2.2 Dielectric properties of water

Liquid water is strongly polar in its structure, causing readily to absorb microwave energy and convert it into heat. The water dipole attempts to continuously reorient towards the oscillating electric field.

Dependent on the frequency the dipole may move in time to the field, lag behind it or remain apparently unaffected. When the dipole lags behind the field then interactions between the dipole and the field leads to an energy loss by heating.

The ease of the movement depends on the viscosity and the mobility of the electron clouds. In water these turns depend on the strength and extent of the hydrogen bonded network. In free liquid water this movement occurs at GHz frequencies (microwaves).[90]

For the water dipole in frequencies between 300 MHz and 20 GHz a constant increasing of its loss factor is observed, i.e. the loss factor of water dipole increase from 2.5 (at room temperature, 300 MHz) to 42 (at room temperature, 20 GHz)[91].

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[90] http://www.lsbu.ac.uk/water.

[91] Vollker Bräutigam, Matthias Graf, Rudolf Emmerich, & Peter Schüller, Mikrowellentrocknung von Wasserlacken „Dielekterishe Eigenschaten von lacksystemen", Carl Hanser Verlag, München, Jahrg.55 (2001) 3, P.53.

Roughly, the difference between the industrial frequencies 2.45 GHz and 915 MHz is the factor 2. Therefore, the heating energy produced by 2.45 GHz is twice higher than by 915 MHz.

The increasing of the temperature leads to a decreasing loss factor for water as shown in Figure 4.16, so that the absorption of electromagnetic energy is decreased, this fact is very important for the evaporation of water molecules.

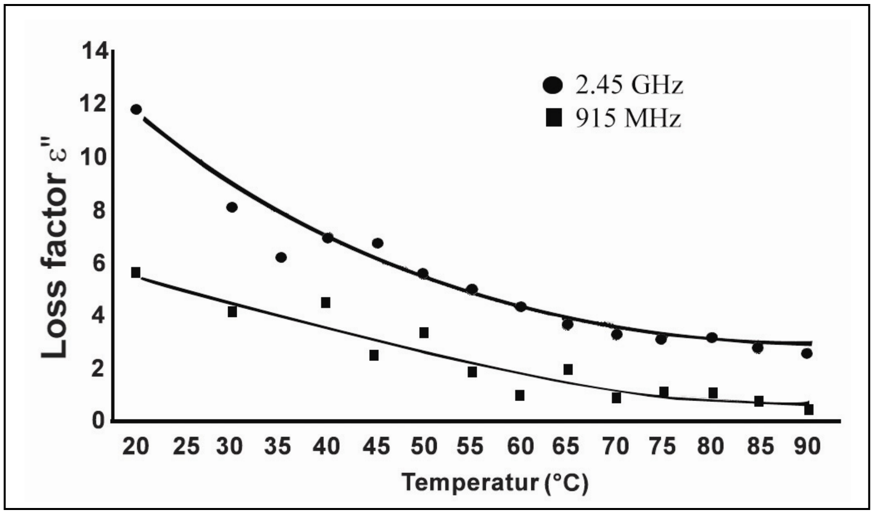

Figure 4.16: The relation between loss factor and temperature of water

This means, the movement depends on the strength and extent of the hydrogen bonded network as shown in figure 4.17.

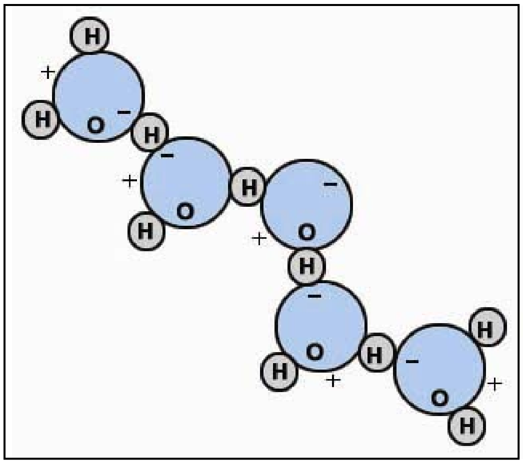

***Figure* 4.17: the hydrogen bonded network in the water molecules**

Chapter 5

The drying of water based ink by microwave -Interaction with substrate-

5.1 Combination between microwave and convection to dry ink films at room temperature

The ideal drying technique of water based inks is to produce heat only onto the printed areas of the paper sheets as long as the ink still contains water, without causing thermal effects on the non- printed areas. This will keep the paper characteristics un-changed.

As mentioned in chapter 4, drying can evaporate directly the water from the wet inked areas. So, microwave can be used to overcome the contradiction between following opposite aims:

- To get away the water from the printed ink film in the printing areas
- To let nearly unchanged moisture content of the paper in the non-printed areas.

To achieve these optimal goals, the temperature of the printed substrate must be kept nearly at room temperature by using air circulation in the microwave applicator. The cooling of the paper web has two advantages:

1. The loss factor (ε'' or ε' tan δ) of water in the ink film (printing ink) is high. From this follows, the absorption of electromagnetic energy and by this the conversion to heat is high as shown in Figure (5.1).
2. The loss factor (ε'' or ε' tan δ) of paper (non-printed areas) is low. From this follows, the absorption of electromagnetic energy and by this the conversion to heat is low as shown in Figure (4.15). In addition, the table (5.1) shows the dielectric properties of paper and water at 2.45 GHz and 20^0C. [90]

This means, generating the needed evaporation heat by microwaves affects directly the water molecules in the ink, but not those in paper.

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[90] TseV.Chow Ting Chan & Howard C. Reader, Understanding microwave heating cavities, Artech House, USA, 2000, P. 251.

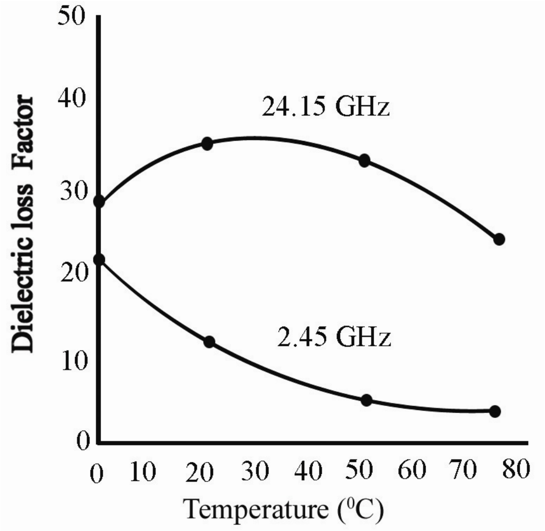

Figure 5.1: Relation between the loss factor (ε") and temperature for water.

MATERIAL	ε′	tan δ
Distilled water	**78**	**0.16**
Paper	**2-3**	**0.15 - 0.1**

Table 5.1: Dielectric properties of paper and water at 2.45 GHz and 20^{0}C.

5.2 Principle of microwave heat generation

In conventional methods of heating or drying, the heat is transferred to the surface of the printed ink film by conduction, convection and/or radiation and into the interior “from outer to inner” mainly by thermal conduction.
The typical heat sources are hot air or infrared heating elements. All of these are located in close proximity to the printed substrate to be heated.

On the other hand, with the microwave drying the heat is generated directly inside the material “from inner to outer “. Therefore, it is possible to obtain a much faster heating effect than in conventional heating. The microwave drying has the following advantages:

1. Microwave heating ensures rapid heat transfers throughout the printed substrate in the electric field, this process is termed as “volumetric heating“. This volumetric heating does not depend on heat transfer through the surface and followed by evaporation of the water from the wet areas as in conventional drying. However, the whole volume of the wet printed areas is heated simultaneously.

2. Because the heat does not have to be conducted into the ink but it is generated inside the wet ink films, the microwave heating reduces the time needed for heating the whole printed surface with a uniform temperature.

3. Microwaves are propagating at the speed of light. As soon as the microwave source is switched on, they immediately penetrate in the wet inked areas to be heated, and the conversion of energy begins. When the source is switched off, the heating process stops immediately. Therefore, long heating and cooling phases are not required.

When the printed web runs through the waveguide applicator, it is exposed to microwave radiation. The E- field penetrates the wet ink film and dielectric losses causes the heat generation. The power dissipation density is given in terms of the dielectric field strength E (V/m) within the printed ink film.

The value of microwave power (P) absorbed in a volume unit of wet inked film on the paper substrate can be calculated by assuming the electric field E established in the wet ink film on the printed substrate as a constant. It is described theoretically according the equations 4.12 and 4.14[91]:

$$\frac{P}{v} = 2\pi f \varepsilon_0 \varepsilon'' E^2 \quad (\mathrm{W/m^3}) \qquad (4.12)$$

whereas:

$$\varepsilon' \tan\delta = \varepsilon'' \qquad (4.14)$$

This equation has two parameters which can be specialized, namely the field strength and the frequency as functions of the energy source. The relative dielectric constant and the loss tangent are properties of the material to be heated. Therefore, increasing the values of these factors would increase the amount of energy to be converted to heat. However it was observed that:

1. the rise in the field strength is restricted by the dielectric properties of the material so that the power loss density can only be increased by increasing the frequency.

2. if the loss factor is low, only a small amount of energy is observed. Therefore, no drying would occur. Conversely, a high loss factor means more absorption and water evaporation.

3. if the electric field is parallel to the printed web, then the electric field inside the printed areas and outside close to its surface are the same.

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[91] A.C. Metaxas & R.J. Meredith, Industrial microwave heating, Peter Peregrinus Ltd, UK, 1983, PP. 73-74.

5.2.1 Time depending of water evaporation from water-based ink by microwaves drying at room temperature

The water inside the ink film is considered to be independently, and it can be separated from the other ink components by expose to electric field inside the microwave dryer. This model is acceptable as long as the electric field is parallel to the ink film. The power dissipation density per volume (p), which is required for the evaporation of the water in the printed ink film, is given according equation (4.12) by:

$$\frac{p}{v} = 2\pi f\ \varepsilon_0 \varepsilon' \tan\delta\, E_{in}^{\ 2}\ , \qquad (5.1)$$

where:
p : is the microwave power absorbed in a small volume element v.
v : is small volume element.
E_{in} : is the internal (in the ink film) electric field strength.
f : is the frequency.
ε_0 : is the permittivity of free space.
$\varepsilon' \tan\delta$: is the loss factor of the dielectric **(ε'')**

As consequence of the evaporation, the volume of the water in the printed ink film is

$$v = \frac{m_w}{\rho} \qquad (5.2)$$

ρ: is the water density
m_w: is the mass of water in the printed ink film.
Substituting (5.2) in (5.1) result is:

$$p = 2\pi f\ \varepsilon_0 \varepsilon''\, E_{in}^{\ 2}\, \frac{m_w}{\rho}\ , \qquad (5.3)$$

where E_{in} is the internal electric field strength in the wet ink film on the web of the paper inside the waveguide. It is being defined as:

$$E_{in} = E_{out} . k \qquad (5.4)$$

Due to basic laws of the electrodynamics, the following standard holds:
If the electric field is perpendicular to the paper, it should be expected for (k) a value near to (1/ε`). on the other hand, if the electric field is parallel to the web, the electric field inside the paper should be as equation[92] (5.5) or k = 1:

$$E_{in} = E_{out} \qquad (5.5)$$

In both cases, equation (5.1) result is

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[92] Ekbert Hering, Rolf, Martin Stohrer, Physik für Ingenieure, Springer- verlag, Berlin , 2004, PP. 284-285.

$$p = 2\pi f\, \varepsilon_0 \varepsilon'' \frac{m_w}{\rho} E_{out}{}^2\, k^2 \qquad (5.6)$$

In addition, we can describe the absorbed power per volume (P/v) which is required for the evaporation of the water in the printing ink film after a specific time as follows:

$$p = -\frac{dm_w}{dt} r\ , \qquad (5.7)$$

where (r) is the specific heat of the water. From (5.6) to (5.7) the equation

$$\frac{dm_w}{dt}\ r = -2\pi\ f\ \varepsilon_0 \varepsilon'' \frac{m_w}{\rho} E_{out}{}^2\ k^2 \qquad (5.8)$$

is obtained then by rearranging follows

$$\frac{dm_w}{m_w} = -2\left(\frac{\pi f\ \varepsilon_0 \varepsilon''}{r\ \rho}\right) E_{out}{}^2 k^2 dt \qquad (5.9)$$

Separation of variables leads to:

$$m_w = m_{w0}\ e^{-\frac{t}{\tau}} \qquad (5.10)$$

with

$$\tau = \frac{r\ \rho}{2\pi\ f\ \varepsilon_0 \varepsilon''} \cdot \frac{1}{k^2} \cdot \frac{1}{E^2{}_{out}} \qquad (5.11)$$

From the equations (5.10) and (5.11) we can conclude:

1 In the microwave dryer the amount of water in the ink goes down exponentially, therefore we can not speak of a drying speed in g/m² s as in the case of convection or infrared drying, but rather about a characteristic drying time τ or a half time, equivalent to (ln 0.5 × τ)

2 The microwave drying process leads to equalize different amounts of water at different locations on the paper substrate. Contrary to conventional drying this may produce to distortions of the printed substrate during a drying process, therefore causing color registration problems.
This means for example: the water in wet inked areas can be dried from 8 g/m^2 to 4 g/m^2. During this drying period the naked paper (70g/ m^2) losses only 0.4 g/ m^2. This achieves negligible changes of the dimensions of the paper.

3. After finishing the microwave drying process, the convection dryer is sufficient for drying the small amounts of the water remained in the printed areas in order to complete the drying process (figure 5.2). This means that microwave drying is the main drying source, specially for the initial drying and should be followed by convection dryer in order to complete the drying process.

4. By drying of carbon black pigmented inks with microwaves, the water evaporation from the ink is larger as with non-conductive pigments, because the carbon black pigmented inks absorbe more electromagnetic energy. Thereby more heating will be generated.

5. As indicated under chapter 4, the loss factor of the paper depends on the temperature and frequency, therefore with low temperature the loss factor is low, and consequently the moisture losses are low. Therefore, the microwave drying is ideal for thick ink films on light weight papers.

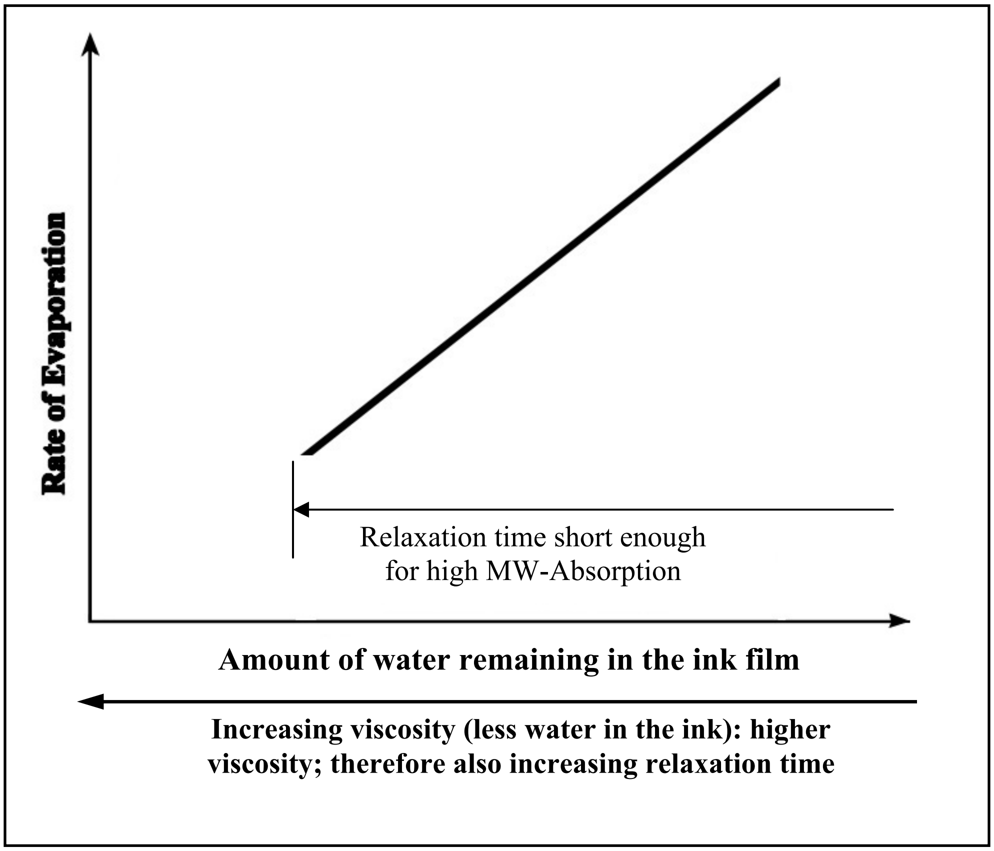

Fig. 5.2: Relationship between the evaporation rate and the moisture content in the printed ink film

Chapter 6
Construction of the microwave dryer system to dry Water-based inks

6.1 Introduction to purpose and planning of the experiment

The aim of this work (as mentioned before in the introduction) is to find a method to reduce the environmental pollution occurred from using solvent based inks.
In this work the use of water based inks without VOCs (Casein inks) for gravure printing instead of solvent based inks was studied.
Literature background survey, which leaded to theoretical considerations, was the first step in this current work. In the experimental part, the proposed solutions of the problems were tested to achieve the following aims:

1. To proof the ability of the microwave drying method to dry the ink in a very short time without large losses of moisture content from the paper. Equation 5.10 for the microwave drying will be confirmed in chapter 7.
2. Chapter 8 will confirm that prints with casein water based inks, after application of a water-based varnish as overprint, have the required dry and wet rub-off resistance.
3. Chapter 9 will confirm that the dynamic of dimension change of the paper substrate after printing with water based inks is much slower than the drying of water based inks with microwave dryer.

Therefore, there are three main areas to be discussed in the following chapters:

1. The construction of a microwave dryer and conducting tests for gravure printing.

2. Printing with VOCs free water based inks. Additionally, the improvement of a good rub-resistance and a high gloss of the printed casein ink films would be achieved through over print with layer of water based lacquers to reduce the environmental pollution caused through the printing inks.

3. Build a device for measuring the dynamic of the dimension change of the paper substrate after printing it with water based inks.

This Chapter is devoted to show the construction of microwave dryer system (MW) which is able to dry the water based coatings and inks without changing the properties of the printed substrate. Section 6.2 describes the construction of the MW dryer system. Section 6.3 describes the preparation process of the microwave dryer system in the printing machine.

6.2 The Microwave dryer system:

As reported in chapter 5 of this thesis, the combination of microwave and convection heating to maintain the temperature at the optimal room conditions of approx. 18- 21°C is considered theoretically as the ideal drying technique. It produces heat only in the printed areas of the paper sheets. This is applicable as long as the ink still contains water, without causing thermal effects to the un-printed areas to keep the paper characteristics without changes. Therefore, a microwave dryer system was constructed as shown schematically in the figure 6.1:

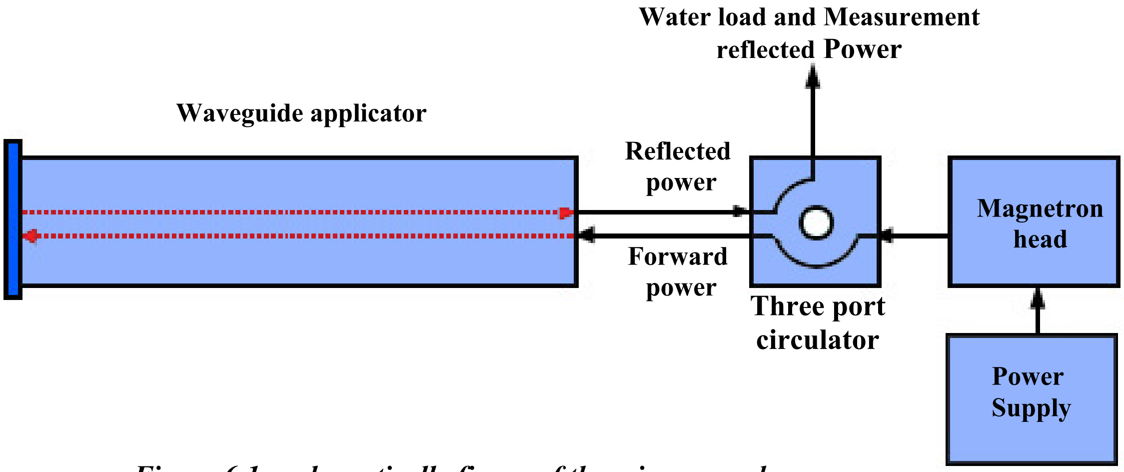

Figure 6.1: schematically figure of the microwave dryer

a- **Microwave generator**: is a key element in the system. Careful consideration should be given to the output power requirement and to the capability for varying the output. The generator should be equipped with measuring capabilities which will indicate both forward and reflected power. The two measurements are necessary so that the actual absorbed power may be determined. The absorbed power is simply the difference between the forwarded power and the reflected power. The microwave generator briefly consists of :

1. **High voltage DC power supply**[93]: It converts the AC line voltage to high voltage DC to power the magnetron. In the experimental work, a power supply was used with the following specifications :
    - Output 3200W max.
    - 3-phase 220V / 60 Hz
    - Internally air-cooled.

---

[93] power supply type: ML2000D-111TG, MUEGGE,Industrial microwave product line, Revision 00, 08.10.2003, muegge d/n do 010,P.71.

2. **Magnetron head[94]:** This is a source of microwave power and is commonly water-cooled. The magnetron head with an output power up to 2 kW cw was applied. The operating frequencies: 2. 45 GHz ± 20 MHz.

3. **Circulator/Isolator[95]:** This is a protection device to avoid the reflected microwave energy from reaching and possibly damaging the magnetron. The isolator will divert the reflected microwave energy to the port with a dummy load.

4. **Dummy load:** This is a microwave-energy absorbing device that is connected to one port of the three-port circulator. The dummy load is normally a water load in higher power configurations. In any case, the reflected energy is dissipated into the load and the microwave energy is given off as heat.

5. **Teflon (TEFL) window:** This device is located between the waveguide applicator and the three-port circulator. The function of this window is to protect the magnetron head /circulator from damage caused by pieces of paper or dust, which are produced as a result of running the paper web through the waveguide applicators during the drying process.

6. **Copper Rods:** These are fixed in a position as small as possible parallel to the electric field and act as a wave reflector to increase the standing wave inside the waveguide applicator.

b- Waveguide applicator: In a microwave system, this device is simply used as a guide for the transmission of the microwave energy from the source to the applicator. In this current work, the dryer system consists of a waveguide with a rectangular cross section (86×43 mm) and slotted at the centre of its broad walls (Figure 6.2) without reducing its ability to keep the fields inside the applicator[96] . The slots are necessary to allow the printed-paper web to run through the applicator (Figure 6.3).

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[94] Magnetron head 2000 W type: MH2000S-211BA, MUEGGE, Industrial microwave, Product line, Revision 00, 08.10.2003, muegge d/n do 010, P.100.

[95] Isolator type: MW1003A-210EC, MUEGGE, Industrial microwave, Product line, Revision 00, 08.10.2003, muegge d/n do 010, P.136.

[96] TseV.Chow Ting Chan & Howard C. Reader, Understanding microwave heating cavities, Artech House, USA, 2000, PP. 225-228.

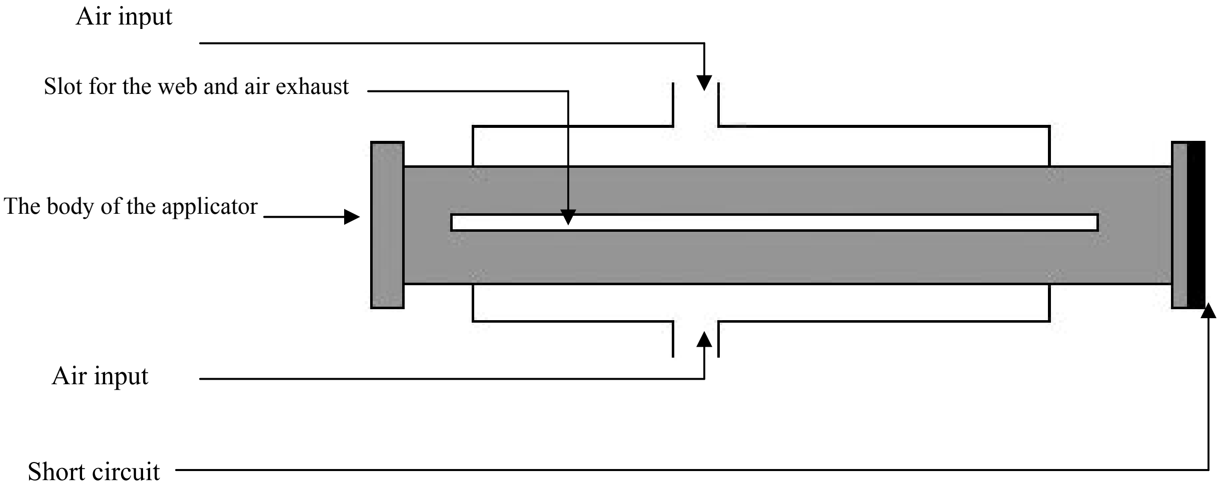

Figure 6.2: The microwave applicator, including a slot for the web and an air input for convection

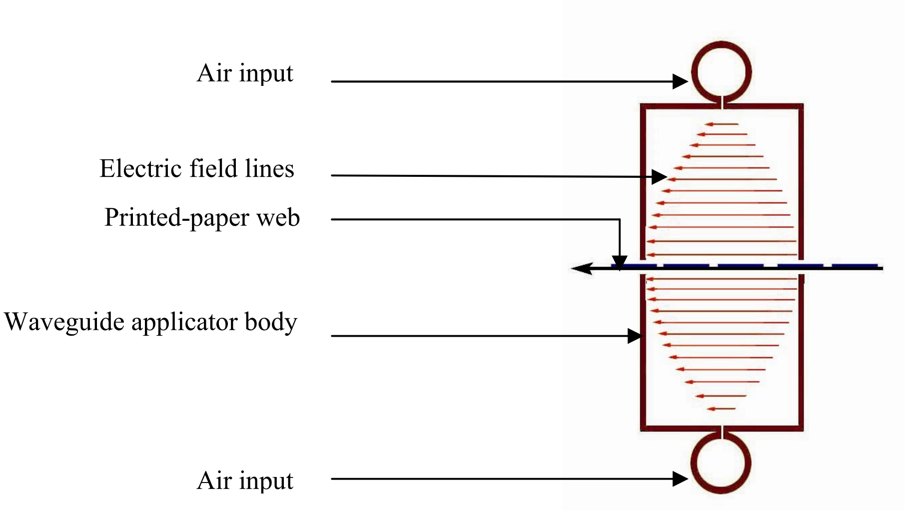

Figure 6.3: Cross-section of the microwave applicator, including a slot for the web and an air input for convection

On the narrow walls of the waveguide are punched holes that feed an adequate air circulation to remove evaporated water from the ink and keep the temperature of the web through convection at room temperature.

Further, the electric fields strength, the air circulation and the status of temperature and relative moisture in the microwave dryer were controlled during the operation.

To measure the electric field strength inside the waveguide, a crystal detector[97] was used. This means, a diode detector is coupled over an antenna and a coaxial line to the electric field in middle the waveguide. The antenna was placed in the slot at of a maximum of the electric field position (Figure 6.4), and the electric current is proportional to the electric field.

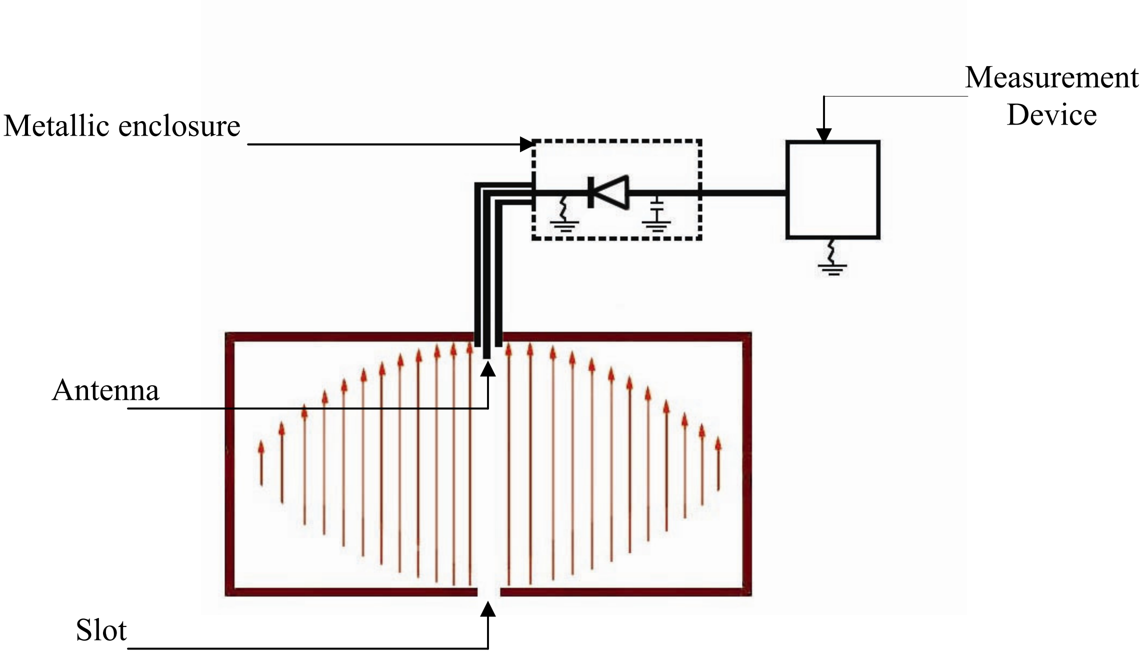

***Figure 6.4:** schematically figure explained the measuring of the electric field inside the waveguide applicator by the diode detector*

6.3 Preparation of the Microwave dryer system in the printing machine

The inks used in the printing trials were water based inks with casein based binder and carbon black pigmentation. Both of the components are non-conductive. The water amount in the ink was about 60 %, with a viscosity corresponding to 21-23 sec. Frikmar 4 mm at room temperature[98]. The preparations of the microwave dryer system in the printing machine to conduct all tests are as follows:

6.3.1 The air convection in the applicator

The air in the dryer was under the recommended standard conditions of 50% relative humidity at 20°C in the whole printing hall[99].

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[97] HP, Crystal Detector, Model 8472 A (NEG), USA.

[98] R. H. Leach, R.J. Pierce, E. P .Hickman, M. J. Mackenzie and H. G. Smith, The printing ink manual, Blueprint, London, 1993, P. 475.

[99] Deutsches Institute für Normung , DIN 50014 -1985-07.

As said earlier the air in the microwave dryer was used to remove the water vapor and to keep low temperature in the waveguide.
It is easy to increase the moisture of the air, but it is difficult to take away the moisture from it. Therefore, the best solution is to transport away the humid air.
In MW dryer, an expanded compressed air was used. The relative moisture in the compressed air after expansion was about 10% because the air losses most of its moisture during the compression process[100].
Therefore, to adjust this dry air from the compressed air supply to the required standard moisture condition, the dry air flowed through water vapor before supplying it to the dryer system as shown in figure 6.5.
It is important to measure this air characteristic regularly during all tests. The amount of moisture added to the air was controlled by the power of the boiler. To measure the temperature and moisture of the air convection inside the waveguide applicator, a sensor was used inside a pipe placed over a hole in the broad wall of the waveguide. These measures give directly the value of temperature and moisture content of the air convection.

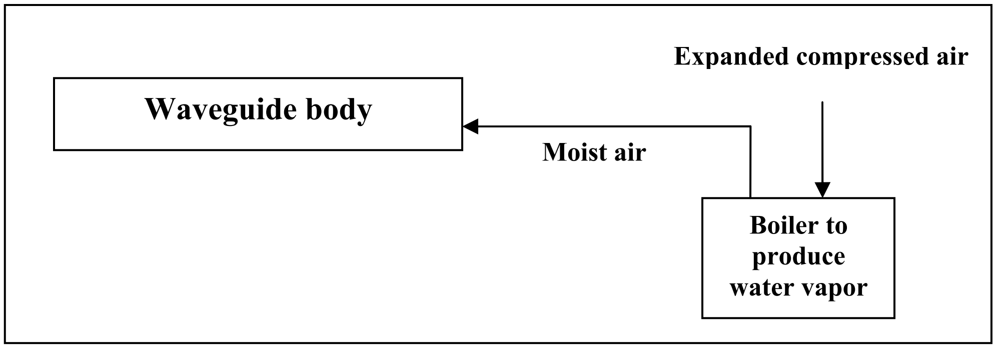

Figure 6.5: the air supply to dryer system

In all measurement printing runs, the air speed and its volume flow were constant, from the Bernoulli equation[101]:

$$\Delta P = \frac{1}{2}\rho_{air} v^2 \qquad (6.1) \quad \text{Then:}$$

$$v = \sqrt{\frac{2\Delta P}{\rho_{air}}} \ , \qquad (6.2)$$

---

[100] Klaus Haase & Johannes Neukirchner, Fachwissen des Ingenieurs Grundlagen des Konstruierens, VEB Fachbuchverlag Leipzig, 1989, PP. 636-637.

[101] Richard P. Feynman, Robert B. Leighton and Matthew Sands, The Feynman Lectures on Physics Mainly Electromagnetism and Matter, 7th Editing , California , USA, 1972, PP.40-6/7.

where ΔP was measured with an easy water manometer in which:

$$\Delta P = h\rho_{water}g \qquad (6.3)$$

h: is the height of the water column

$$v = \sqrt{\frac{2gh\rho_{water}}{\rho_{air}}} \quad . \qquad (6.4)$$

For all our experiments the air speed corresponded to a (ΔP) of 0.4 bar subsequently:

$$v = 245 \text{ m/s} \qquad (6.5)$$

The air speed at the nozzles is expected to be about 245m/s but its magnitude at the web surface is much lower with more amount of the air which moved towards to the web through in “air jet ejector pump effect”[102]. A measurement with a “dummy” has shown over about 60 m/s[103].

6.3.2 The electric field in the waveguide applicator

The measurements were done at the maximum of the standing wave in the applicator. This maximum, corresponding to a sinus function is relatively wide. The samples were taken from areas at these positions to measure the relative water losses from the printed and non- printed areas.

Copper rods were used at the minima to increase the standing wave in the waveguide; in addition, a diode detector was used to indicate the electric field strength in the waveguide.

The measurements were done over the current from the diode detector as shown in figure 6.4.

Table 6.1 shows the measurements of the forward and reflected power of the power supply and the current from the diode detector.

These measurements were done with and without reflecting rods.

	Forward power	Reflected power	Current from crystal detector
Without reflecting rod	50% from 2 k W	48.1 %	2.4 m A
With one rod	50% from 2 k W	45.8%	6.2 m A
With two rods	50% from 2 k W	41.8%	9.8 m A

Table 6.1: the forward and reflected power of the power supply and current from the diode detector with and without reflecting rods

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[102] www.svs-gmbh.de/english/prod02.htm.

[103] Private communication with Prof.Dr .Rodriguez Giles.

For the TE_{10} in the rectangular cross-section waveguide the relation between the amplitude of the electric field of the traveling wave and the power is given by[104]:

$$E_{max} = \sqrt{\left[\frac{4P}{a \cdot b} \cdot \frac{\lambda_g}{\lambda_0} \cdot \left(\frac{\mu_0}{\varepsilon_0}\right)^{\frac{1}{2}}\right]} \qquad (6.6)$$

Where:

P : is the forward power in (kW)
$a.b$: is the cross section of the waveguide in centimeters (cm^2)
λ_g : is the waveguide wavelength in centimetres (cm)
λ_0 : is the wavelength of free space in centimeters (cm)
μ_0 : is permeability of free space
ε_0 : is permittivity of free space

At the maxima of the standing wave[105], which results from the reflected power P as shown in figure 6.1, the equation 6.6 can be written as:

$$E_{max} = 2 \cdot \sqrt{\frac{4P}{a \cdot b} \cdot \frac{\lambda_g}{\lambda_0} \cdot \left(\frac{\mu_0}{\varepsilon_0}\right)^{1/2}} \quad . \qquad (6.7)$$

Consequently, with forward power one kW (50% from 2 kW) the maximum electric field strength is 480 V/cm.
The current from the crystal diode detector is proportional to the electric field, and the relation between the electric field and this current is:

$$E_{max} = K\,I \quad , \qquad (6.8)$$

where: K is a proportionality constant = 200 (V/cm)/mA. Table 6.2 shows the measured values of E_{max} in V/cm and the corresponds current in mA inside the waveguide

I_{max} (m A)	E_{max} (V/cm)
3.4	680
5	1000
6.2	1240
7.2	1440
8.1	1620

Table 6.2: E_{max} with* V/cm *and correspond Current with* m A *in the waveguide

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[104] Roger Meredith, Engineers' Handbook of industrial Microwave Heating, IEE, UK, 1998,P.112.
[105] B.M.Jaworski, A.A. Detlaf, Physik griffbereit Definitionen Gesetze Theorien, Friedr Vieweg+Sohn , Braunschweig, 1972, P.531.

A WG 340 waveguide[106] may be used to transmit up to 25 k W (the forward power), in this case the electric field strength reached to 1200 V/cm without danger of each discharge or other problems. Most of the measurements were done of about 1240 V/cm. The efficiency of the microwave dryer (this means the share of the MW-power absorbed used to evaporate water from the ink) may be 50% or more.

6.3.3 The drying time of the printed web in the electric field

The printing tests were done at speeds from 10 m/min up to 40 m/min. This means, the remaining time of the printed web in the waveguide (MW dryer) can be shown as in table 6.3. These time values were calculated from the following equation:

$$v = \frac{b}{t} \qquad (6.9)$$

Where:

- v: is the printing speed in (m/min)
- b: is the narrow side of waveguide in (cm)
- t : is the remaining time in the waveguide in (s)

printing speed (m/min)	remaining time (sec.)
10	0.258
20	0.129
30	0.086
40	0.065

Table 6.3: Printing speeds and remaining time of the printed web in MW dryer

6.4 Measurement techniques

In this set up, the dryer system was prepared to work by setting the copper rod in the minima position of the standing wave and the crystal diode indicator in the maxima position to measure the electric field strength inside the waveguide applicator. The setting of moisture and temperature sensor was placed on an overhead hole of the waveguide to indicate and measure the blown air characteristics to ensure that the air stream inside the waveguide is still at 20^0C/ 50% rh.

As seen earlier in chapter 5 equations 5.10 & 5.11, combined with microwave electric field and air convection to keep the temperature inside the dryer at room temperature, the amount of water in the ink goes down exponentially:

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[106] Roger Meredith, Engineers' Handbook of industrial Microwave Heating, IEE, UK, 1998, P. 113.

$$\frac{m_W}{m_{W0}} = e^{-\frac{t}{\tau}}$$

Actually (mw/mw$_0$) is the relative losses of water in the ink film. As consequence of the microwave drying, this equation can be written as follows:

$$\frac{m_{W0}}{m_W} = e^{\frac{t}{\tau}} \tag{6.10}$$

E$_{out}$ is the electric field in the waveguide E, therefore equation 5.11 may be written as follows:

$$\tau = \frac{r \quad \rho}{2\pi f\ \varepsilon_0 \varepsilon'' k^2 E^2} \tag{6.11}$$

If we represent for $\frac{m_{W0}}{m_W}$ as symbol (u) then;

$$\ln(u) = \ln\left(\frac{m_{WF0} - m_{WP}}{m_{WF} - m_{WP}}\right) \tag{6.12}$$

Where: $$m_{W0} = m_{WF0} - m_{WP} \tag{6.13}$$

With:

m_{WF0} : Weight loss in the oven of printing areas without MW-drying

m_{WP} : Weight loss in the oven of un-printed paper, and:

$$m_W = m_{WF} - m_{WP} \tag{6.14}$$

With:

m_{WF} : Weight loss in the oven of printing areas with MW-drying

$$\ln(u) = \quad \ln\left(\frac{m_{WF0} - m_{WP}}{m_{WF} - m_{WP}}\right) = \left(t \cdot \frac{2\pi f\ \varepsilon_0 \varepsilon''}{r \ \rho}\right) k^2\ E^2 \tag{6.15}$$

Where τ is the characteristic drying time, from (6.10) and (6.11), and from all equations mentioned above; the drying measurements were based on a maximum of the standing wave to do the following tests:

1- test if the ln(u) values increases linear with (t) values for a fixed value of (E)

2- test if ln(u) increases linear with (E^2) for a fixed value of (t) and then from the slopes (a) as in the following curves of the drying measurements section for ln(u) function of (E^2), it can be estimated the value of the constant k.

6.5 Estimation of moisture content in the experimental tests

The gravimetric measurement[107] was used to estimate the change of the moisture content. This method is the standard way of determining the moisture content, in which the printing paper is initially weighed and then dried in an oven at $103 \pm 2\ ^0$C for 30 minutes.

The loss in weight during drying indicates how much water was originally present in the printed sample (from the printed areas: 4,6,8,12,18 μm) and the moisture content can be calculated simply as the follows:

$$\text{Moisture content (\%)} = \left(\frac{m_{before} - m_{after}}{m_{after} - m_{alu}} \right) \times 100 \qquad (6.16)$$

Where:

m_{before} = the weight of the printed sample before drying treatment
m_{after} = the weight of the printed sample after drying treatment
m_{Alu} = the weight of the aluminum foil piece to wrap the printed sample

The gravimetric measurement was applied to estimate the moisture content as it is the only measuring method not affected by the pigmentation (as IR -methods) or the place where the water molecules attached at fibers of paper (as microwaves moisture measuring devices).

The following equipment was used to estimate the moisture losses from the printing and non printing areas:

1. Balance for weighing the test samples, the balance should have a capacity about 200g and be capable of detecting difference of 0.005g. In the experimental trials was used a digital balance[108] which give an instantaneous reading (figure 6.6).

2. The oven drying requires a well ventilated oven[109] (figure 6.7) which can control the temperature between 101°C and 105°C.

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[107] Deutsches Institute für Normung e.V., DIN EN 20287-Die übersetzung der international Norm ISO 287 , Papier und Pappe Bestimmung des Feuchtegehaltes Wärmeschranksverfahren, sep. 1994.

[108] METTLER, Analysenwaagen,Mettller Toledo AG,CH-8606 Greifensee, Switzerland.

[109] Memmert – UL 30-770519- 854 Schwabach.

Figure. 6.6: Analysis weighing apparatus

Figure 6.7: Oven drying apparatus

Chapter 7

Drying measurements of water-based coating and ink by using microwave dryer

7.1 Experimental setup

The aim of the experimental work is to confirm that the combination of microwave irradiation with convection leads to a drying of the water in the ink. As well as the moisture of the paper remains nearly without changing.

As mentioned in chapter 6 of this thesis, microwave electromagnetic fields were build-up in a hollow metallic tube as microwave dryer system. In addition, this dryer system was fixed on a gravure laboratory web press for conducting experiments; to set the relevant process magnitude drying time without changing the applicator. It produces a microwave field over a width of about 4, 3 cm. Table 7-1 shows the factors investigated in the experimental work.

Input variables and levels							
		Factor levels					
System	**Variables**	**1**	**2**	**3**	**4**	**5**	**Units**
Press	Speed	10	20	30	40	-	m/min
Cells depth	Nominal ink film	4	6	8	12	18	μm
Electric field strength (Amplitude)	Drying efficiency	680	1000	1240	1440	1620	v/cm
Paper web	Weight	70	75	80	-	-	g/m^2
Paper web	Color	White		Black		Creme	
Ink	Color	Yellow-red	Blue	Red-yellow	Black	-	-

Table 7.1: the factors used for experimental work

7.2 Design of the press:

In the trials, a 30 cm web was printed from a RK gravure-printing machine[110] by using engraved anilox cylinders with various cell depths as shown in table 7-2, to apply water-based inks and lacquers.

As seen in figure 7.1 the schematic diagrams for the anilox and impression cylinders with a correct mounting for the doctor blade.

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[110] Handbook of the RK printing, Coating and laminating machine, RK print-coating instruments limited, Lillington, Royston, Herts., SG8 0QZ.

7.2.1 Inking system:

The amount of ink, and thereby the water on the paper was determined by the engraving of the anilox cylinders as described in table 7.1.

With these cylinders a solid tone was printed with different ink film thicknesses.

Table 7.2 shows the ink film thickness on the paper with corresponding amounts of water on the paper.

Gravure thickness (for 100% transferred ink film) [µ]	**Water in the actually transferred ink film 100 % solid area [g/m²]**
4	1.4
6	1.8
8	3.7
12	4.4
18	6.1

Table 7.2: The ink film thickness on the paper corresponded to the following amounts of water on the paper

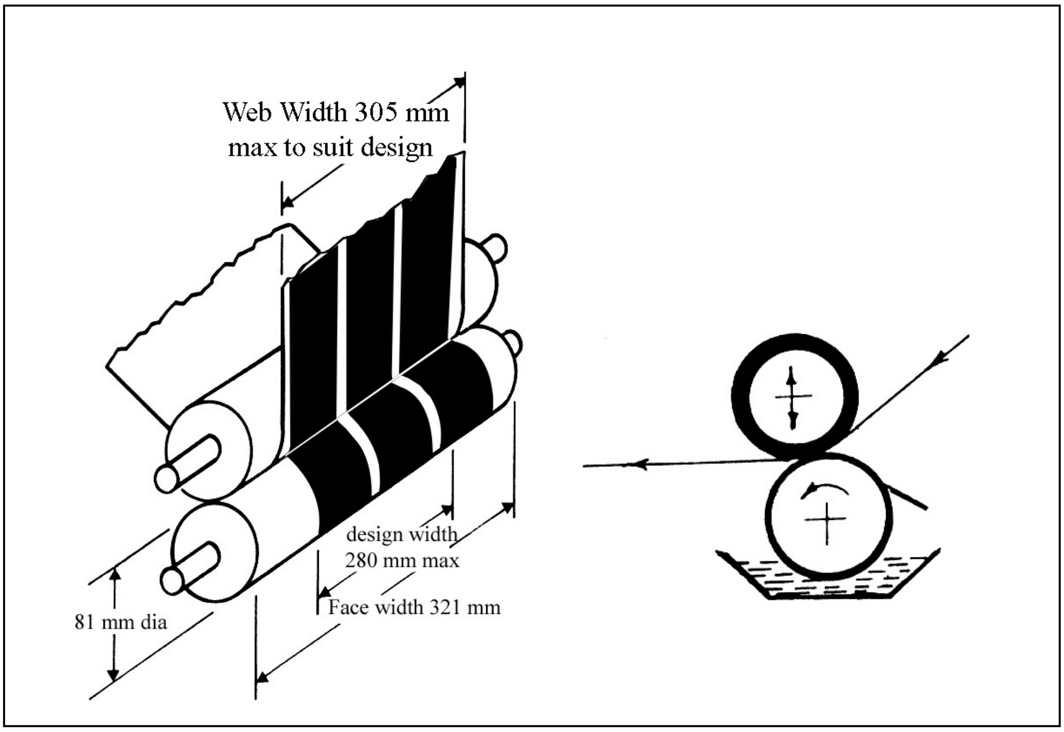

Figure 7.1: Design of the press and inking system

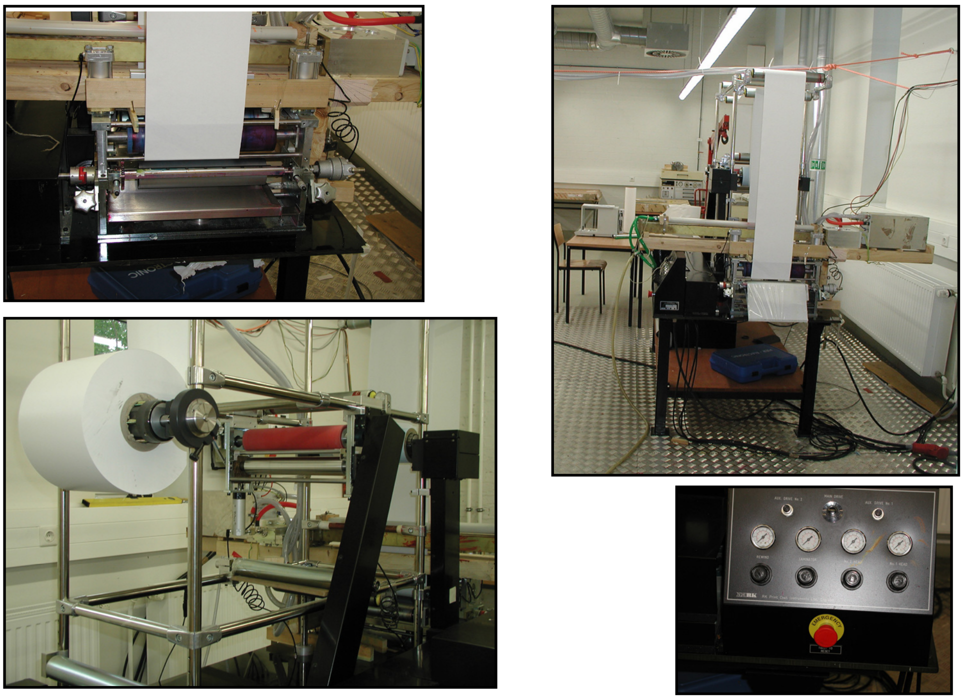

Figure 7.2: The RK printing, coating and laminating machine (RK print-coating instruments limited)

7.2.2 Inks

Water based inks with a casein based binder having non-conductive pigmentation (especially no carbon black) were used in the measurements as shown in table 7.3(a). Contrary to other water based inks, they do not dry irreversible. Therefore, they do not contain ammonium or amines.

The water amount in the ink was about 60 %, with a viscosity corresponding to 21- 23 s measured with a Flow cup 4 mm[111] at room temperature.

These inks from Hartmann & Sun chemical were produced specially for Interprint GmbH, Arnsberg, Germany.

Yellow red G 4938 / 741	**Red yellow RW R 9477 / 741**
H 75796 / 791	**Red ink 600-420**
Blue 1117 / 761	**Blue green 11224 / 741**

Table 7.3 (a): Water based inks (Casein binder)

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[111] Elcometer Frikmar viscosity cups, the cup is first dipped into the product to be measured, then empties through of orifice, the measured kinematic viscosity is generally expressed in seconds flow time, kinematics viscosity and drain times mentioned above are approximate value at 25 ^{0}C exact value will be displayed on the standard oil bottle.

For comparison reasons, a carbon black pigmented ink was used as well, as shown in table 7.3(b):

Black ink 420 /702
Black S 2101 / 741

Table 7.3 b: Black water based inks (Casein binder)

7.2.3 Printed substrate

A paper reel of "Technocell Dekor Germany"[112] was used for different tests; these papers have the following characteristics:

- A grammage of 60, 70 and 80g/ m²
- Uncoated surface
- 3- 4% moisture content in the paper
- Different colours: Cream, white, and black (includes carbon black)
- Having about 30% of filling material[113].

These decoration-papers are light weight uncoated papers nearly without any other additives except for the vegetal fibers and filling material. Therefore, they have a pronounced tendency to web-breaks.

7.3 Measurement of the relative water losses from the printed ink film as a function of time for different ink film thicknesses

In this part, the relationship between the relative water losses from the printed ink film and its remaining time in the microwave dryer were studied. These printed ink films were conduced in different thickness of color ink, black ink and pure water to make a comparison between water in the ink as solvent and the pure water.

7.3.1 Measurements of printing with a color ink (Reddish-yellow ink non-conducting pigment)

The dryer system was fixed on a gravure laboratory web press for conducting experiments. It produces a microwave field over a width of about 4.3 cm. The electric field strength in these measurements group is constant at 1240 [V/cm], these measurements group were conducted in four different printing speeds namely 10, 20, 30 and 40 m/min.

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[112] Hell Braun Interprint 60,70,and 80 g/m^2, Technocell Dekor, Ein Unternehmen der Felix Schoeller Gruppe, Germany.

[113] Private communication with Dr. David, Interprint company, Arnsberg, Germany, 06-2006.

Actually, the relevant process magnitude is the drying time; this means the time needed by the web to cross the microwave field, this time is equal to the waveguide width divided by the web speed.

Two anilox cylinders were used to conduct the printed solid tones with different ink film thickness, one of both has a gravure engraving 4 µm, 6 µm, and 8 µm, and the second anilox cylinder has 12 µm and 18 µm, by these anilox cylinders have been printed with different casein water based inks is Hartmann ink RW G4938/741.

The gravimetric method was used to estimate the change of the moisture content of the printed areas before and after drying as indicated previously in experimental setup.

These measurements were conducted to characterize the response of the dryer system to remove the half amount of the water content from the printed areas.

Results

We compute with average amount of moisture content in the paper about 3 g/m^2, actually, it changes from one place to another about up to ±0.15 g/m^2. Especially with low amounts of ink (thin ink film) and therefore low amount of water, to be dried the variation of moisture in the paper may lead to larger relative errors by finding the value of the logarithms of the relative water losses from the printed ink film ln(u). Therefore, we compute in all measurements the amount of moisture in the paper as a constant equals 3 g/m^2.

It can be shown from table (7.4) and figure (7.3) the dependence of the relative water loses over the time needed by a surface element of the web to cross the waveguide applicator.

A linear increase of the logarithm of the relative water loses should be expected.

time	6µm	8µm	12µm	18µm	Mean
0	0	0	0	0	0
0,063	0,4055	0,4162	0,4383	0,3542	0,4035
0,084	0,4353	0,4964	1,0116	0,6931	0,6591
0,126	0,5878	0,7138	1,0986	0,9076	0,8269
0,252	1,0296	1,126	2,0541	1,6964	1,4765

Table 7.4: The relationship between the drying time and the relative moisture losses for reddish-Yellow ink with different ink thickness

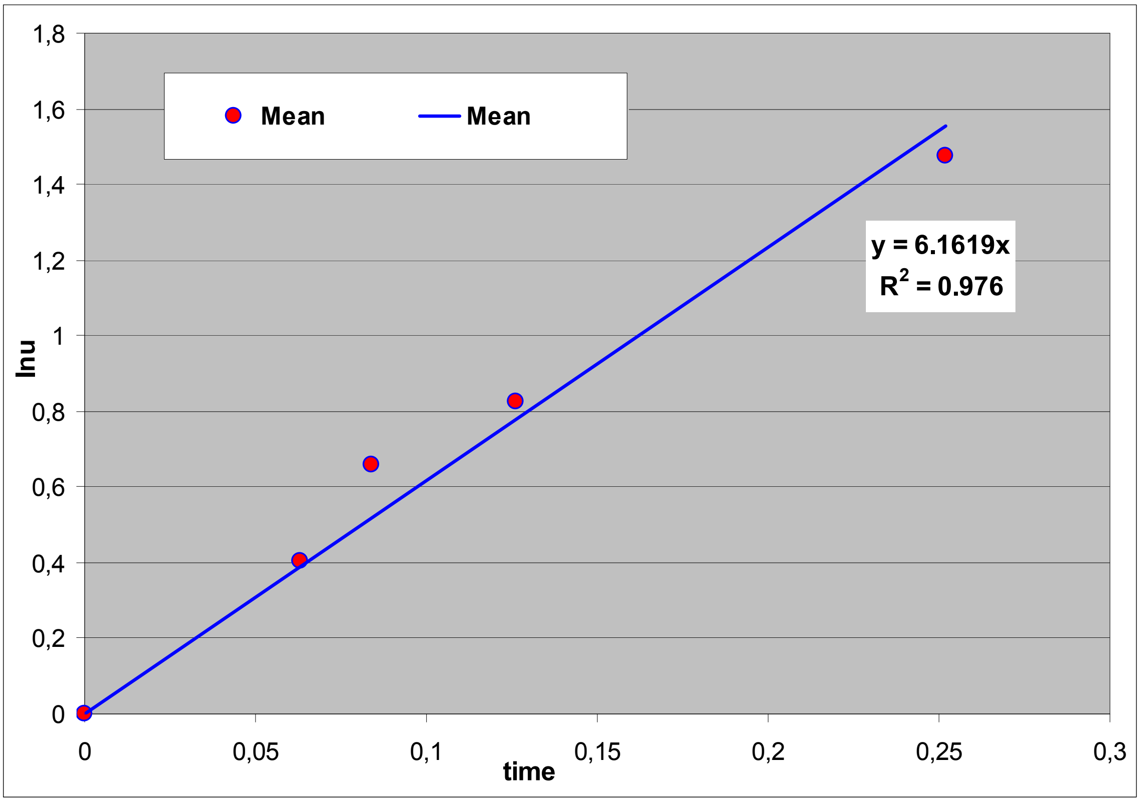

Figure 7.3: The relationship between the drying time and the relative moisture losses for reddish-Yellow ink with **different ink thickness**

It can be seen from the table 7.4 and figure 7.3 that with the larger ink film thickness as for 8, 12 and 18 µm is well fitted by straight line, indicating that the microwave dryer has advantages to drying water based inks compared with conventional drying methods. By using a microwave dryer, the evaporation of water increases with increase of ink film thickness. This is a result of high dielectric losses of the water molecules in the ink film and absorption of the electromagnetic energy as well as converting it into heat.

7.3.2 Measurements of printing only with water

As assumed before in chapter five of the theoretical considerations, the water as solvent in the ink would interact with the microwave field as the same of pure water; therefore a comparison with the drying of pure water is relevant.

Pure water was applied on the web with the gravure press in runs with the cylinder that has engraving depths 4, 6 and 8 µm.

Results

Table 7.5 and figure 7.4 confirm that the relative water losses are independent from the initial amount of water. The results become a linear relationship between the relative water losses and the remaining time in the microwave dryer as in theoretical studies mentioned in chapter 5.

Time	6µm	8µm	Mean
0	0	0	0
0,063	0,3216	0,2591	0,2903
0,084	0,3814	0,3406	0,361
0,126	0,8329	0,5039	0,6684
0,252	1,674	1,1558	1,4149

Table 7.5: The relationship between the drying time and the relative moisture losses for pure water with different thickness

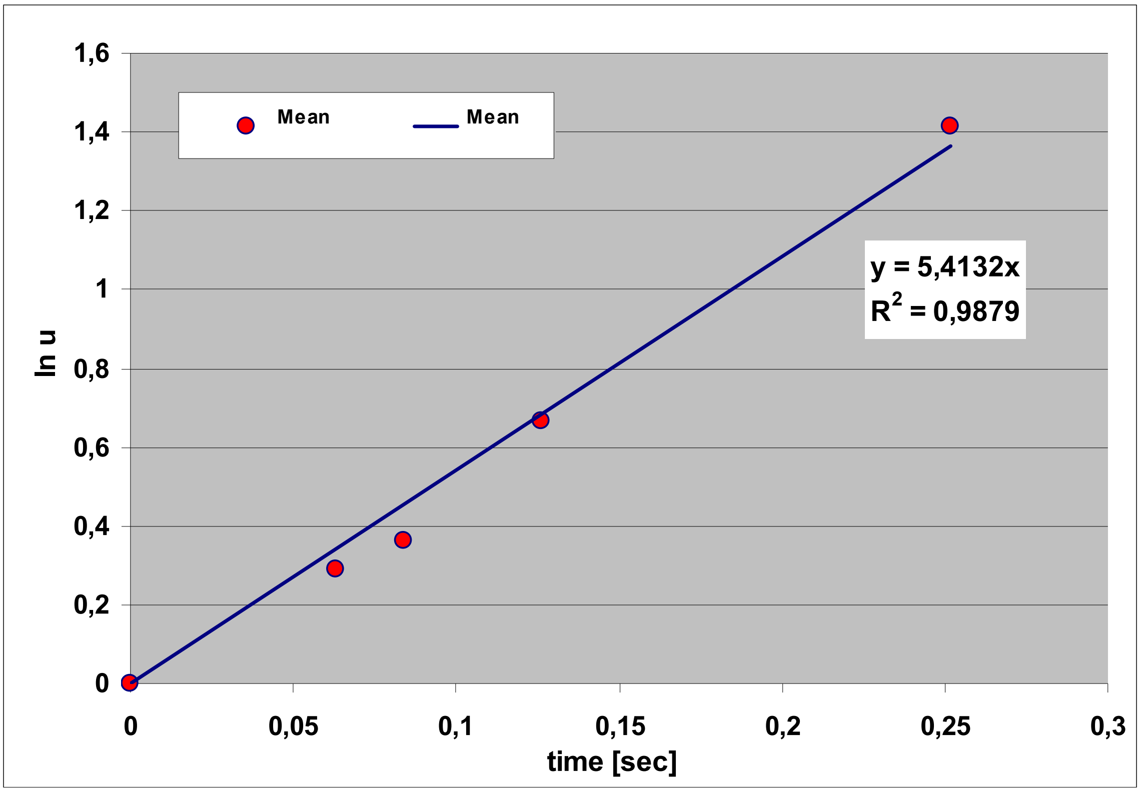

Figure 7.4: The relationship between the drying time and the relative moisture losses for pure water with different thickness

It can be seen in the figures: the slope is comparable as for water based ink figure 7.3 and for water figure 7.4, the lower slope may be explained as consequence of the absorption of water molecules in paper bulk: the water molecules attached to the cellulose fibers absorbs less of microwave energy as those in liquid water or ink. Actually, this attachment of water molecules to the fiber leads to an immediate change of dimensions of paper which will be examined in chapter 9.

7.4 Measurements of the relative water losses from the printed ink film as a function of the electric field strengths

These measurements were conducted to confirm the effect of changing value of electric field strengths inside the waveguide applicator on the drying of the printed substrate. The electric field strength was varied from (680 V/cm) to (1620 V/cm) and measurements were done by using the setup described in equation (6.15). These measurements were classified as follows:

- Relative water losses as a function of the drying time for two different electric field strengths.
- Relative water losses as a function of the electric field strength for a drying time of 0.129 second.
- Relative water losses as a function of the electric field strength for a drying time of 0.064 second.

7.4.1 Measurements of relative water losses from the printed ink film as a function of drying time for two different electric field strengths.

In these measurements, two electric field strengths and their effect on the drying characteristics were compared. The aim of these measurements is to confirm the relationship between the relative water losses from a printed ink film and the time for the printed web in the electric field inside the waveguide applicator.

The measurement set up was as in previous experimental measurements except that only one cylinder was used with engraving depths 12 μm and 18 μm.

Results

For both fields there is a linear relationship between the logarithmic relative moisture losses and the time for a surface element of the web in field (drying time inside the E-field), without dependence over on the initial ink film thickness. The slope increases with the electric field as in table 7.6 and figure 7.5.

Time (s)	12/18(6.1 m.A)			12/18 (8.1 m.A)		
	12µm	18µm	Average	12µm	18µm	Average
0	0,00	0,00	0,00	0,00	0,00	0,00
0,063	0,36	0,35	0,36	0,69	0,68	0,69
0,084	0,80	0,69	0,75	0,82	0,83	0,82
0,125	0,88	0,91	0,89	1,27	1,34	1,31
0,172	—	—	—	1,59	1,50	1,54
0,252	1,48	1,70	1,59	2,40	2,36	2,38

Table 7.6: The relationship between the drying time and the relative moisture losses for two electric field strengths

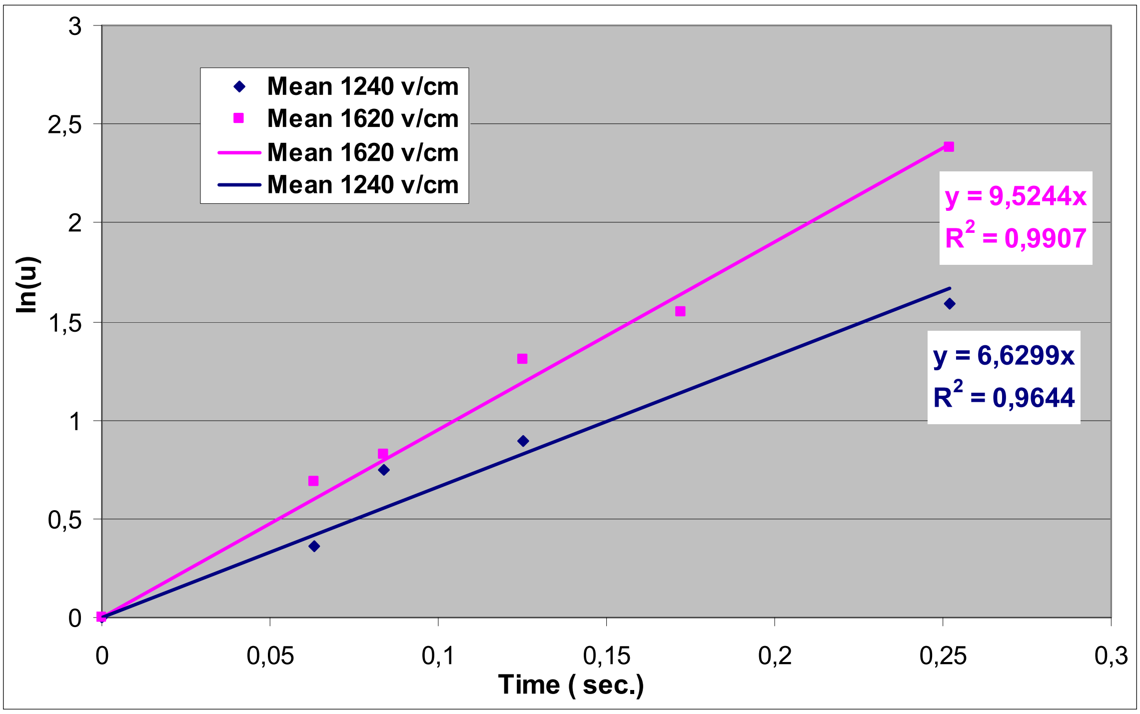

Figure 7.5: The relationship between the drying time and the relative moisture losses for two electric field strengths

7.4.2 Measurements of relative water losses from the printed ink film as a function of the electric field.

The aim of these measurements is to confirm the relationship between the electric field strength from 680 V/cm to 1620 V/cm and the relative water losses from printed ink film. The measurement set up was as for previous experimental measurements with using the anilox cylinder with engraving depths of 12 μm and18 μm. The chosen drying times were 0.129 and 0.064 second.

7.4.2.1 Results achieved during the period of 0.129 and 0.064 second

For a given time in the microwave-field the value of ln (u) is proportional to E^2, as it should be expected form equations (6.10 and 6.15).

As shown in table 7.7 and figure 7.6, there is a linear relationship between the logarithms to relative moisture losses and the electric field strength E_{out}^2 in the waveguide applicator which is parallel to the printed web running through it without depending on the initial ink film thickness. The slope increases along with the electric field.

	ln(u)					
	12μm		18μm		Mean	
E^2_a (v/cm)	0.129 sec.	0.064 sec.	0.129 sec.	0.064 sec.	0.129 sec.	0.064 sec.
0	0	0	0	0	0	0
4.6×10^5	0,2	0,1	0,2	0,1	0,2	0,1
10×10^5	0,52	0,18	0,52	0,18	0,52	0,18
15.4×10^5	0,92	0,37	0,92	0,37	0,92	0,37
20.7×10^5	2,4	0,41	2,4	0,41	2,4	0,41
26.2×10^5	—	0,59	—	0,59	—	0,59

Table 7.7: The relationship between the relative water losses from the printed ink film and the different electric field strength for a drying times of 0.129 and 0.064 second.

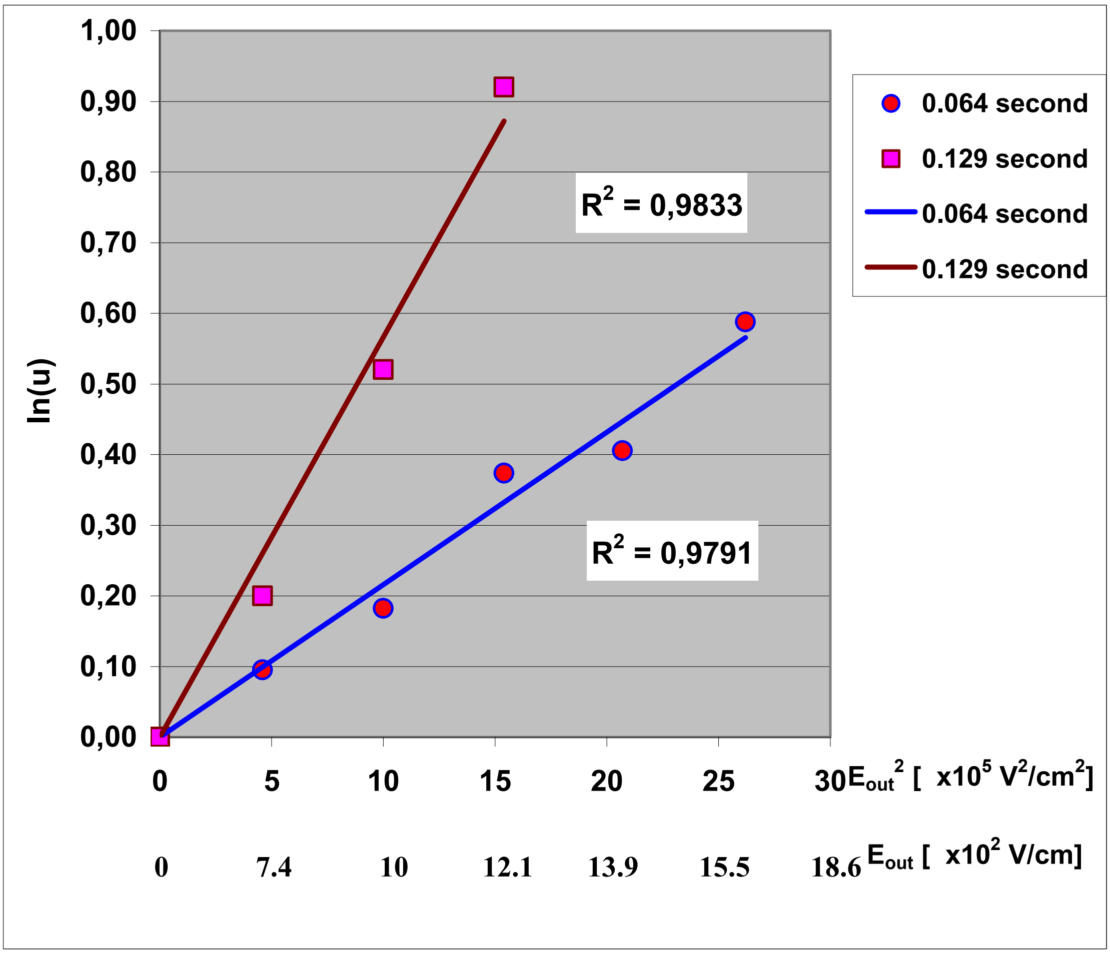

Figure 7.6: The relationship between the relative water losses from the printed ink film and the different electric field strength for a drying time of 0.129 and 0.064 second.

7.4.2.2 Estimation of the value of k

The value of k could be estimated from the slope of ln(u) as a function of E^2 for fixed times of the web in the applicator as seen in figure 7.6 from the following relation:

$$\frac{\ln u}{E_{out}^2} = \frac{2\pi f\, \varepsilon_0 \varepsilon'' t}{r\,\rho} \cdot k^2 \qquad (7.1)$$

Solving for k:

$$k = \sqrt{\left(\frac{\ln u}{E_{out}^2}\right) \cdot \left(\frac{r\,\rho}{2\pi f\, \varepsilon_0\, \varepsilon''\, t}\right)} \qquad (7.2)$$

The value of ε''for the wet printed ink film is not known and it should be assumed that it changes value during the printing and drying processes. Therefore by sub in equation7.2 for ε'' with the well known value for water at 25^0C is (ε'' = 13), the

computation leads to results for k well over 2. As written in chapter 5, k must be ≤ 1; more exactly, as the electric field is parallel to the ink film should be k near to 1.
This can be interpreted as:

1. The value of k is near to the maximum possible value, this means it is near to1.
2. The actual value of ε'' for ink is well over the value for water as consequence of the presence of ions in the water based ink, see figure 4.13.

7.5 Measurements of moisture losses from unprinted paper as a function of time for paper substrates with / without carbon black.

These measurements were conducted to study the effect of different color paper substrates on absorption of the electromagnetic energy inside the waveguide applicator. This means that to measure the losses of the moisture from the non-printed paper (non-printing areas) as a function of time. These measurements were done for cream color and black paper substrates both of them have 80 g/m^2 with moisture content about 3 g/m^2.
The measurement set up was as for previous measurements, the non-printed paper web-cream color and black paper- running through the microwave dryer with different speeds from10 m/min up to 40 m/min. The electric field strength was 1240 (V/cm).

Results
From figure 7.7 it can be seen that the black paper (containing carbon black) absorbs more electromagnetic energy than cream colored paper but without effect on the non printed paper (non-printing areas).
It can be also seen from figure 7.7 that the carbon black in the paper substrate has more effects on the moisture losses from the paper.

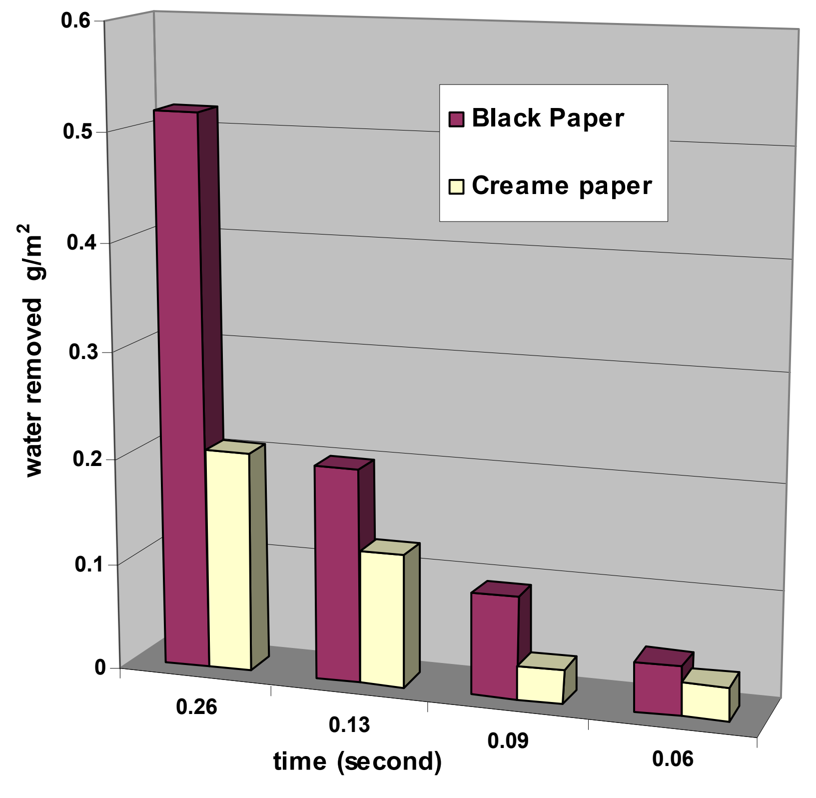

Figure 7.7: The relationship between the drying time and the relative moisture losses for two different color of paper substrate

7.6 Measurements of the moisture losses from unprinted paper as a function of time for different weights of the paper substrate

These measurements were conducted to study the effect of different paper substrate weight (grammage) on absorption of the electromagnetic energy inside the waveguide applicator. This means measuring the losses of the moisture from the non-printed paper (non-printing areas) as a function of time for different weights of the paper substrate 60 g/m^2, 70 g/m^2, 80 g/m^2, all have moisture content about 4.3 %.

The measurement set up was as for previous measurements, the non-printed paper web-with different weight 60 g/m^2, 70 g/m^2 and 80 g/m^2- running through the microwave dryer with different speeds from10 m/min up to 40 m/min. The electric field strength was 1240 (V/cm).

Results

From the figure 7.8, it can be seen, that in the microwave dryer system the absorption of electromagnetic energy is proportional to the amount of water molecules in paper substrate, therefore the paper weight 80 g/m^2 has more moisture losses than 70 g/m^2 and 60 g/m^2.

But these moisture losses from the non-printed areas inside the microwave dryer are very small. Therefore, the microwave dryer does not leave a negative effect on the non-printing areas. This means that, the microwave dryer leads to keep the moisture content of the paper substrate nearly without any change. This result is important to avoid all folding and finishing problems which may occur from the thermal effects which are known by use the conventional dryers.

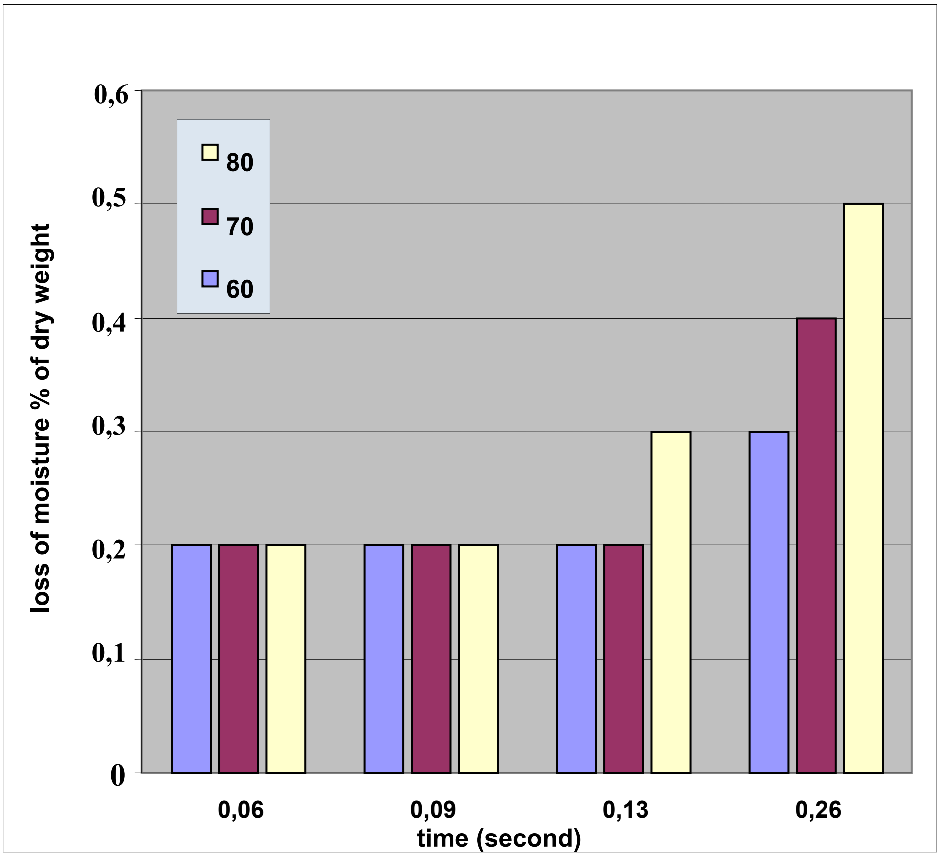

Figure 7.8: The relationship between the drying time and the relative moisture losses for different paper substrate weights

Chapter 8
Measurements of the overprint coatings

8.1 Introduction to the purpose of rub-resistance test:

Once the ink has been printed, it is important to find out that the printed ink film which has the proper durability to withstand the condition. The evaluation of ink durability can begin through one of some different tests done for each type of ink. The tests are as the following:
1. Abrasion resistance
2. Chemical resistance (colour transfer)
3. Outdoor durability

To evaluate the varnish overprint and ink durability in this work, an abrasion (rubbing) resistance test was used.

Rubbing is the effect of repeated relative shifting of two contacting surfaces under a certain pressure. The resistance of material to rub-effect is known as rub-resistance.

The rub-resistance test leads to damages of the relatively thin film of the ink (or varnish on ink) in those positions and contamination of the non-printed parts of the paper.
The importance of this test is not only at the actual output of paper from the printing machine, but even more so consecutive stages as during finishing operations or rubbing against each other during shipping or handling. The printed surface is subject to a rubbing action that tends to wear or scratch the printed surface.

There are two types of rub-resistance test: dry and wet rub-resistance. Dry rub resistance is critical on products such as retail bags and bread bags, as the exposed ink film is abraded and scuffed during end use.

Wet rub resistance is very important for frozen food bags, which can be subjected to abrasion during handling. Both wet and dry rub are a function of ink film integrity and bonding to the substrate. By using casein inks, which do not dry in an irreversible way a low wet and dry rub- resistance should be feared and should be improved by varnish layer as explained in chapter three.

Rub is influenced by amount of the applied ink, chemical composition of the ink, drying mechanism, and ink substrate interaction.

As consequence, to improve the quality of the printed products other set preliminary investigations were conducted to determine the experimental variability of dry (DRR) and wet (WRR) rub-resistances of the dried water-based inks by applied water based lacquer varnish to improve the rub resistance.

8.1.1 Input and output variables:

The specifications of the used water based varnish (lacquer) are:

- Terrawet[114] Barrier lack G 9/421
- Terrawet Barrier lack G 9/469

This water-based lacquer improves not only the gloss and rub-resistance but is also considered as a safe chemical layer on the food packages.

Input variables and levels				
		Factor levels		
System	**Variables**	**1**	**2**	**Units**
Lamination Layer	Rub-resistance	Dry	Wet	Wear or scratch

Table 8.1: the factors used for experimental work

Selections of the output measures are driven by understanding of attributes that define the print quality by water based inks (the quality of the drying process).
The measurements were classified according to the following tests:

1. measurements of the wet rub resistance
2. measurements of the dry rub resistance

For both of these measurement groups, the samples were coated with different varnish liquids, as well as with different varnish thickness.

8.2 Equipment of method:

A motor driven rub-resistance tester[115] was used to conducting all measurements as seen in figure 8.1. This device moves a weighed test specimen over the printed sample. Typically, a 610g weight with 5 cm diameter was used to provide a contact pressure. The rub resistance is then given as the number of rubs required to break through the printed surface.
Because of the many variations of the printing substrates, inks used, and manner of application, it is impractical to establish a single standard number of rubs. Standard should be set for each individual application.

8.2.1 Dry rub-resistance:

For conducting this test, printed or varnished printed samples (strips) with size about (5× 15 cm) must be obtained. The 15-cm direction should be cut from the across direction of the sheet and must not cross wrinkles, creases or other imperfections that would distort the results.
A circular shape with diameter about 3 cm of the un-printed stock from the same run was adhered to the rubbing cylinder.

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[114] Flyer of TERRA LACKE, Joachim Dyes Lackfabrik GMBH, Lehrte , Germany.

[115] Handbook of the Prüfbau – Dr. ing . H. Düner – 8123 Peißenberg – München.

The print side up of the test specimen (printed sample) was mounted on the rubbing pad of the base plate. In addition, the weight-rub cylinder was centered on the printed sample.
After placing the weight over the sample, the weight-rub cylinder oscillated against the printed sample from 5 to 100 strokes, or less if a failure observed by the contamination of the un-printed rubbing paper.
The results were expressed as the percent of contaminate on the un-printed sample.

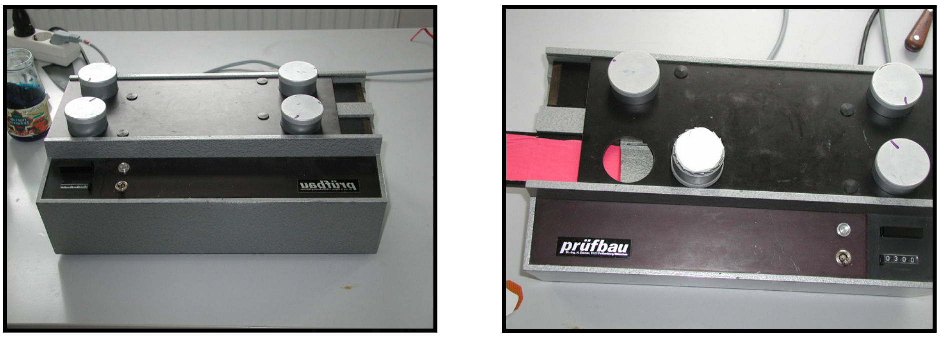

Figure 8.1: the rub resistance Tester

8.2.2 Wet rub-resistance:

For the wet rub resistance test, the printed strips were built up in the same manner as for the dry rub test. For each testing, up 2 to 6 drops of distilled water were first placed on the printed surface at the start of the test. It must be examine the failure observed as contamination of the un-printed rubbing paper after one stroke. In addition, each repeated single stroke which leads to ink failure was noted and recorded, as well as the number of strokes.

8.2.3 The evaluation of the rub-resistance tests:

The printed failure was determined by transferred color from the printed substrate to the un-printed substrate. The higher of the stroke numbers (at which the sample fails), the better the rub resistance.

To obtain a numerical reading of the degree of rub, or to evaluating of both the dry and wet rub-resistance, the following procedures were used:

- The unprinted rubbed paper scanned with a flat-bed scanner[116] with 300 dpi resolutions to generate a picture file as input for a picture processing program[117].
- Convert the picture mode of this file to CMYK mode. Then activating the channel of the identical ink color (cyan, or other process color).

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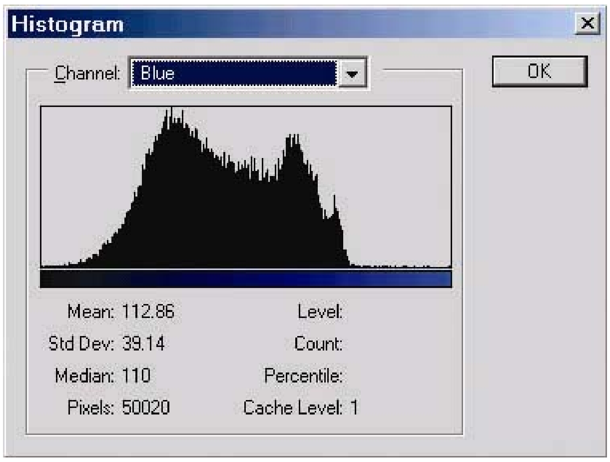
[116] Handbook of the *Agfa* DouScan ® flat-bed scanner.

[117] Handbook of the ADOBE® PHOTOSHOP® 6.0 Copyright (c) 1989-2000 Adobe Systems Incorporated, USA.

- By use of the ellipse-selection-tool the surface area of rubbed printed sample was selected.
- Adjust the threshold at 254 from the picture schedule setting.

- Through the function Histogram (figure 8.2) the relationship between the stained pictures parts (Pixel) and the non-stained parts (Pixel) can be obtained as a percentage.

- If this value is little percentage this means, the printed ink film or varnish is more constant to rub-resistance.



Channel: Blue

Mean: 112.86
Std Dev: 39.14
Median: 110
Pixels: 50020
Level:
Count:
Percentile:
Cache Level: 1

Figure 8.2- (a): ***The Threshold tool reduces images to simple black-and-white bitmaps***

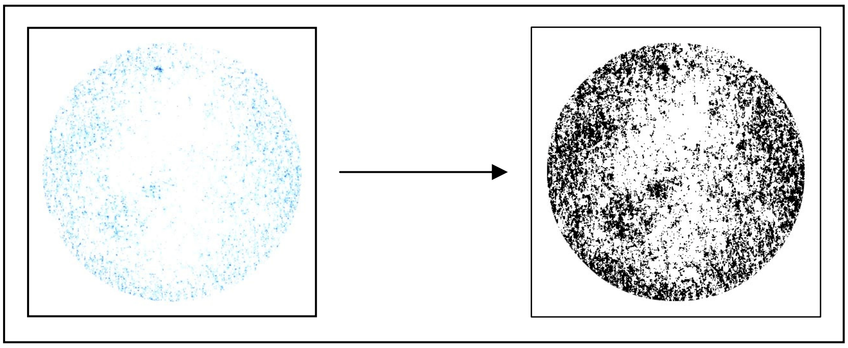


Figure 8.2- (b): ***Shows by use of the Histogram tool it can be estimate the rub off tests.***

8.3 Measurement of irreversible drying water based ink

This measurement was conducted to measure dry and wet rub-resistance of a water based ink, manufactured in Egypt under the trade name Pakin ink without using lacquer over print. This ink is irreversible drying water based ink.

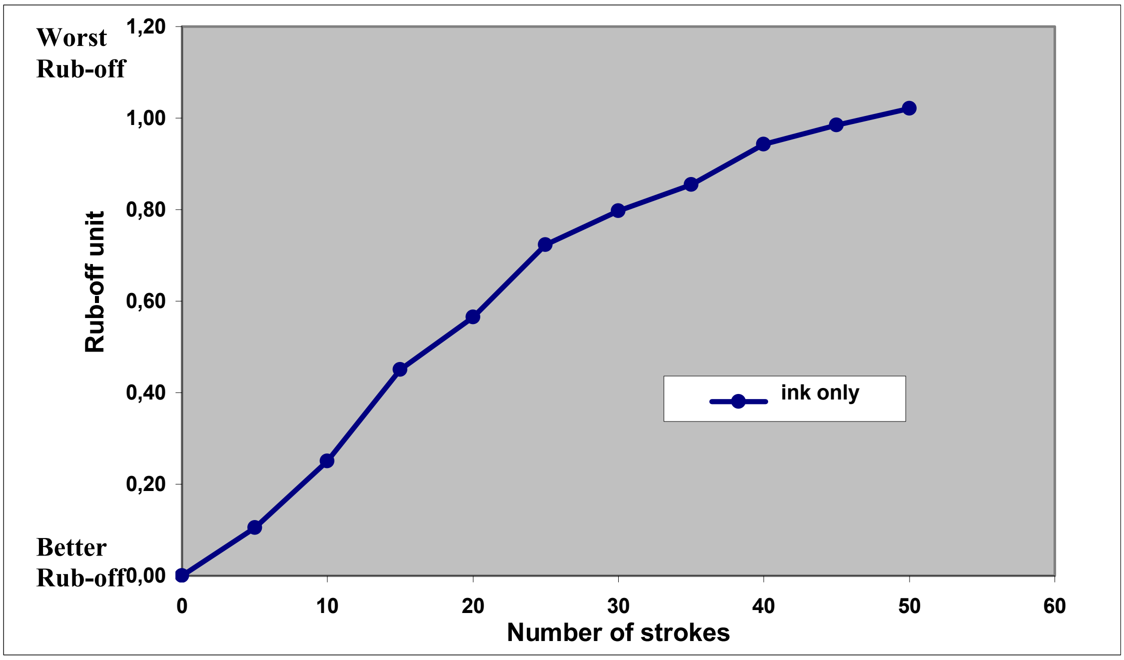


Figure 8.3: the relationship between the number of strokes and dry rub-resistance
For irreversible drying water-based ink without lacquers overprint

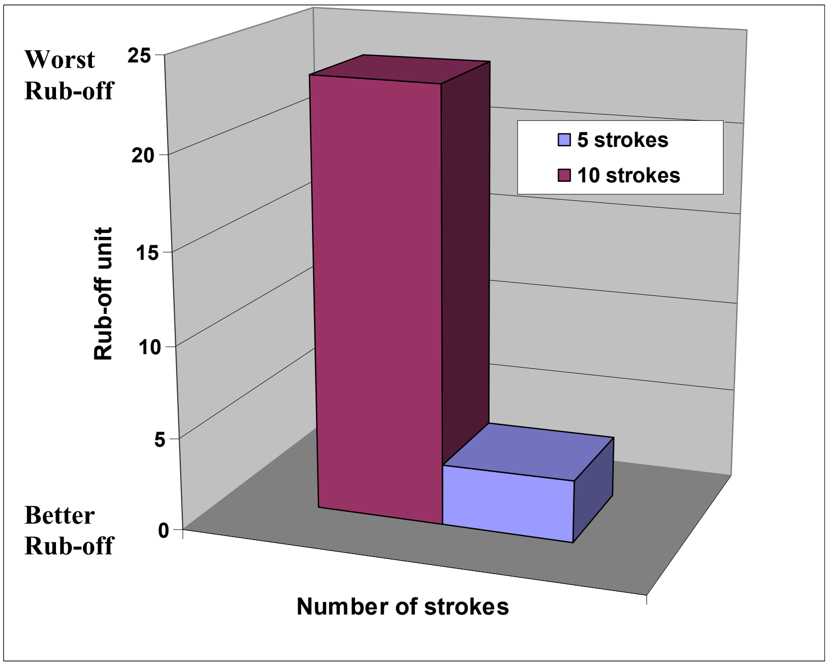


Figure 8.4: the relationship between the number of strokes and wet rub-resistance
For irreversible drying water-based ink without lacquers overprint

Results

It can be seen from the figure 8.3 and 8.4 that, the resistance to rub-off is always the same, but the wear of the ink film goes on with the increases of the stroke number.

8.4 Measurement of reversible drying water based ink

These measurements were conducted to illustrate the effect of the varnishes to enhance the dry and wet rubbing-off casein inked film after printing on the substrates.

These printed samples were carried out in the laboratory[118] and the varnished overprint by using meter bar applicator laboratory machine[119]with three different thicknesses of layers 4, 12 and 24µm.

These measurements were classified in two groups measurements the dry and wet rub-resistance of the coating with normal adhesive and water base lacquers (varnishes).

8.4.1 Measurement of the coating with normal adhesive

8.4.1.1 Measurement of the coating with commercial dispersion glue

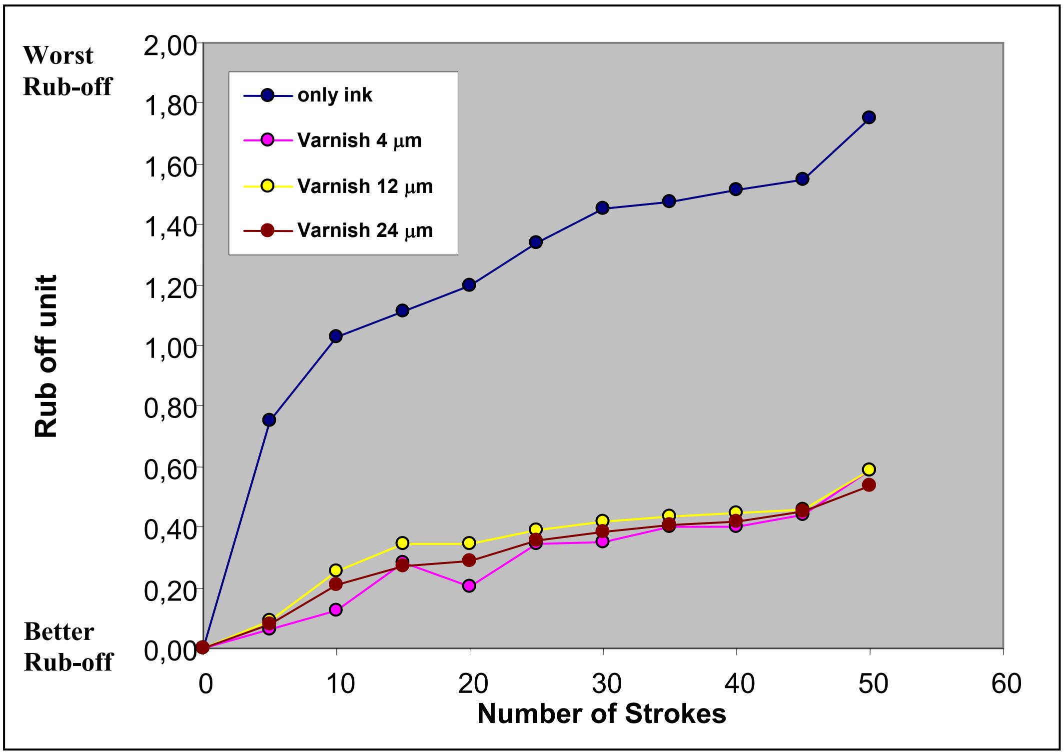


Figure 8.5: the relationship between the number of strokes and dry rub-resistance For Casein water based ink with commercial dispersion glue overprint

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[118] Handbook of the gravure proofer, Courtesy of RK print-Coat instrument Ltd.,UK.
[119] Handbook of the Meter bar applicator machine, Courtesy of RK print-Coat instrument Ltd.,UK.

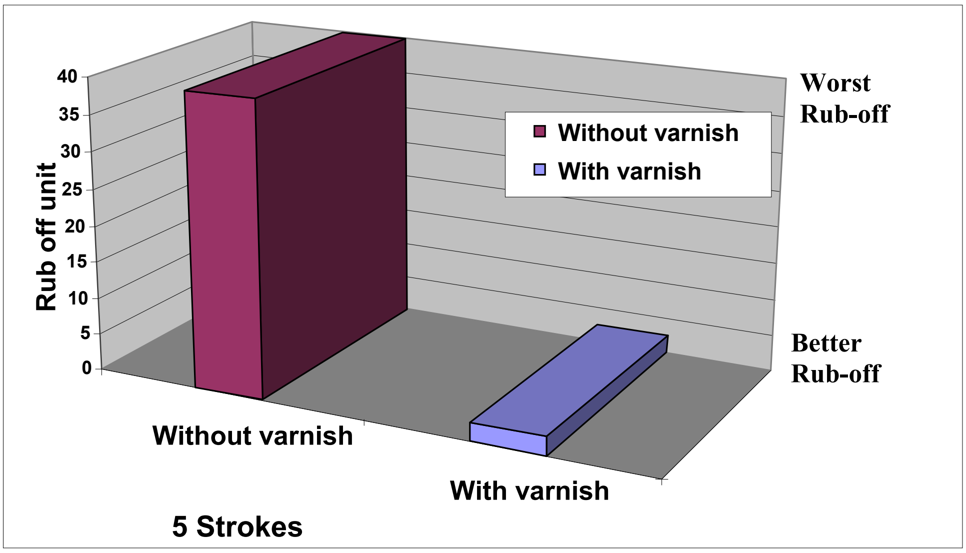

Figure 8.6: the relationship between the number of strokes and wet rub-resistance
For Casein water based ink with commercial dispersion glue overprint

Results

It was estimated that the rub-resistance of all these measurements by comparing the tint effects which resulted from the rubbing off processes.
Figure 8.5 shows the dependence of dry rub-off with and without varnish overprint (adhesive dispersion glue) on the printed samples with water based ink. It can be seen that the resistance for rubbing off the ink film increases initially with the increase of the varnish film thickness from 4 µm to 24µm and decreases without varnish overprint (ink film only).
Figure 8.6 shows the dependence of wet rub-resistance on the varnish overprint, it can be seen the tint effect which result from the rubbing off of ink film only was extremely great comparing with tint effect from the rub-off the ink film plus varnish overprinted.

8.4.1.2 Measurement of the coating with a commercial flexography adhesive

This measurement was conducted as in preview measurement but here to examine effects of a commercial flexography adhesive to enhance the dry rubbing off the casein ink film after printing on the substrates.

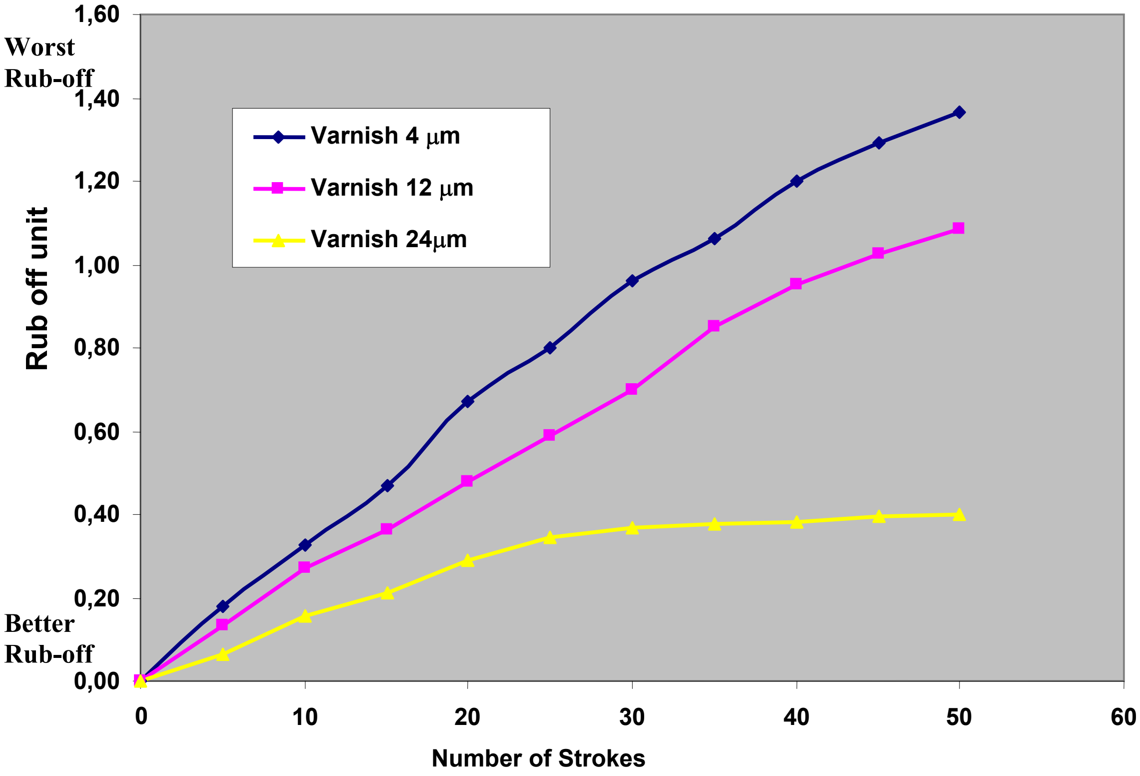

Figure 8.7: The relationship between the number of strokes and dry rub-resistance
For Casein water based ink with commercial flexography adhesive overprint

Results

Figure 8.7 shows the dependence of dry rub-resistance of the varnish overprint (with a commercial flexography adhesive) on the printed samples with water based ink. It can be seen that, the resistance for rubbing-off the ink film increases initially with the increase of the varnish film thickness as seen in figure from 4 µm to 24µm, this means the rub-resistance of printed samples with relatively thick layer as in 24µm has an excellent resistance to dry rubbing off.

8.4.1.3 Measurement of the coating with a commercial offset adhesive

This measurement was conducted as in preview measurements but here to examine effects of a commercial offset adhesive to enhance the dry and wet rubbing off the casein ink film after printing on the substrates.

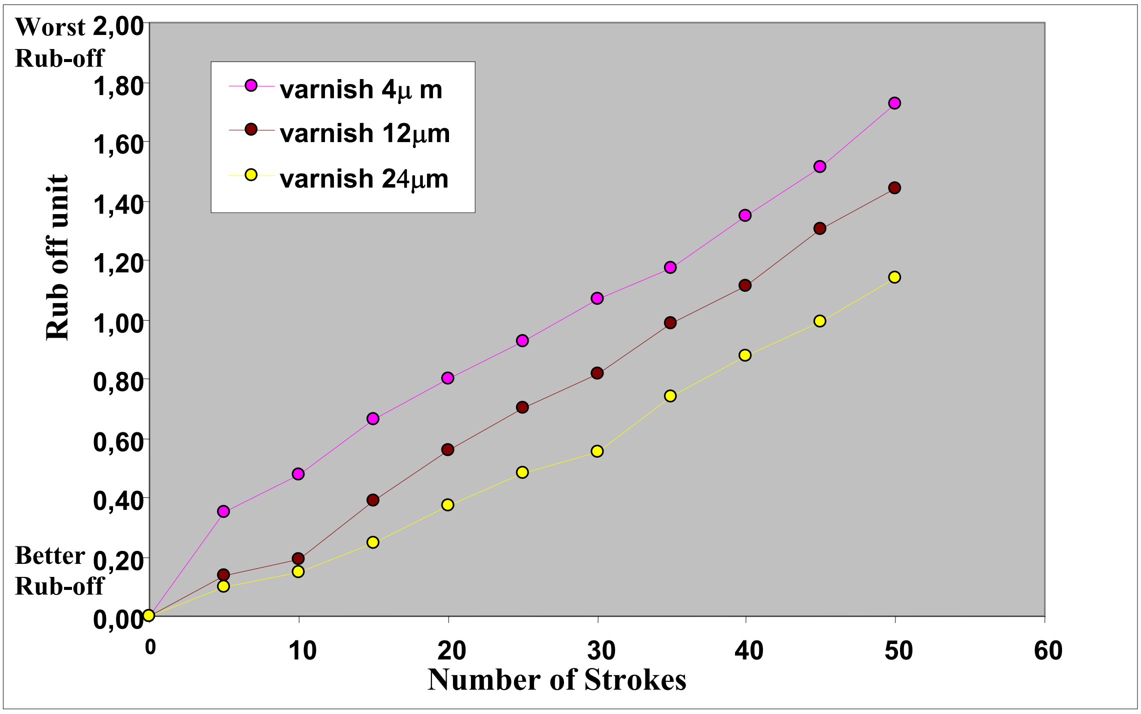

Figure 8.8: The relationship between the number of strokes and dry rub-resistance
For Casein water based ink with commercial offset adhesive overprint

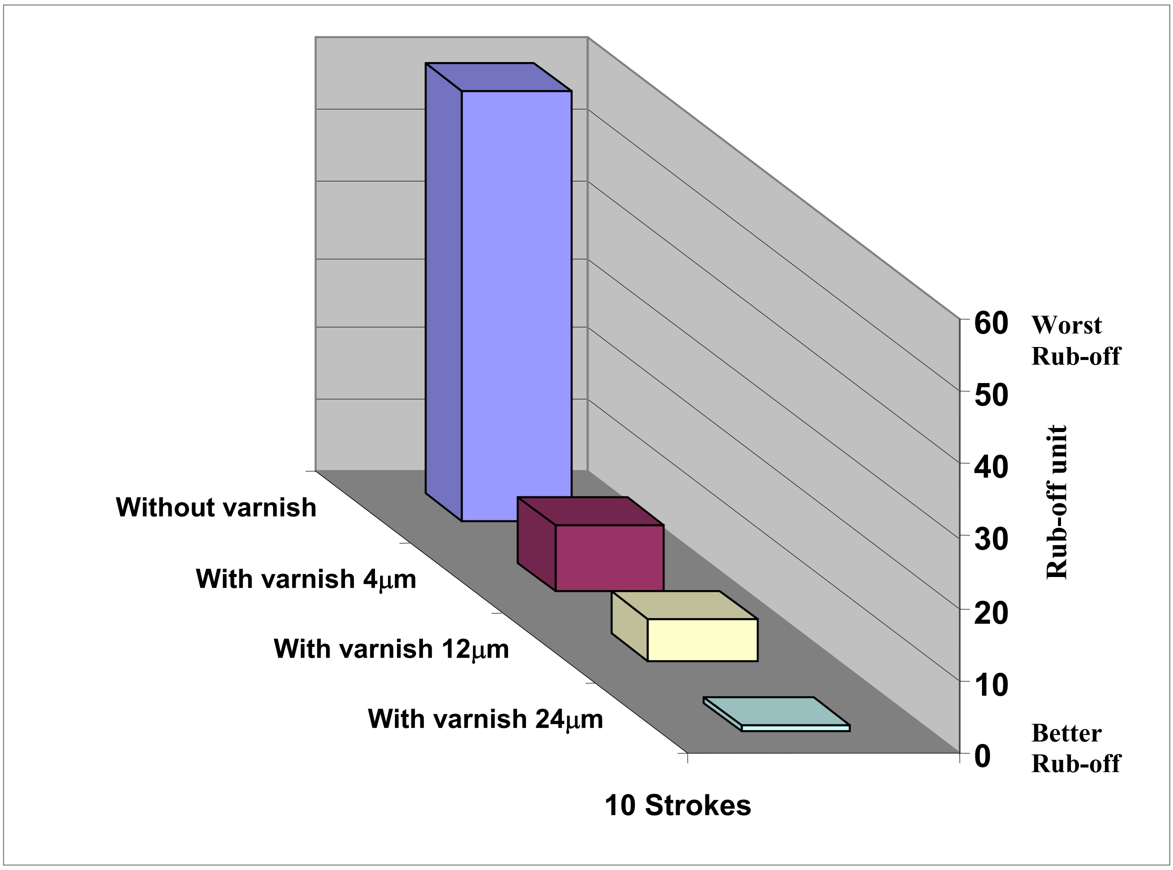

Figure 8.9: The relationship between the number of strokes and wet rub-resistance
For Casein water based ink with commercial offset adhesive overprint

Results

Figure 8.8 shows the dependence of dry rub-resistance of the varnish overprint (with a commercial offset adhesive) on the printed samples with water based ink. It can be seen that the resistance for rubbing-off the ink film increases initially with the increase of the varnish film thickness as seen in figure from 4 µm to 24µm.
Figure 8.9 shows the important of the over print layer to enhance the wet rub-resistance of printed ink film.
The increase of overprint thickness leads to an increase of rub-resistance for this overprint layer.

From figures 8.5 to 8.9 it can be observed that, by applied normal adhesive (commercial offset adhesive, commercial dispersion glue and a commercial flexography adhesive) as overprint on the dried ink film; the results of the dry rub-resistance (Figure 8.5, 8.6 and 8.8) are excellent but the wet rub-resistance is very bad as in figures 8.6 and 8.9.

8.4.2 Measurement of the coating with water based lacquers

This measurement was conducted as in preview measurements to examine effects of water based lacquer G9/469 and G9/421 to enhance the dry and wet rubbing off the casein ink film after printing on the substrates. The results are shown in the following figures:

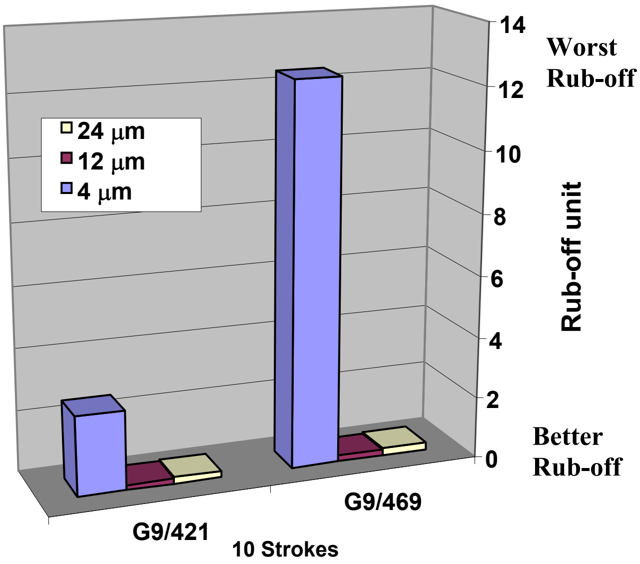

Figure 8.10: The relationship between the number of strokes and dry rub-resistance
For Casein water based ink with water based lacquers overprint

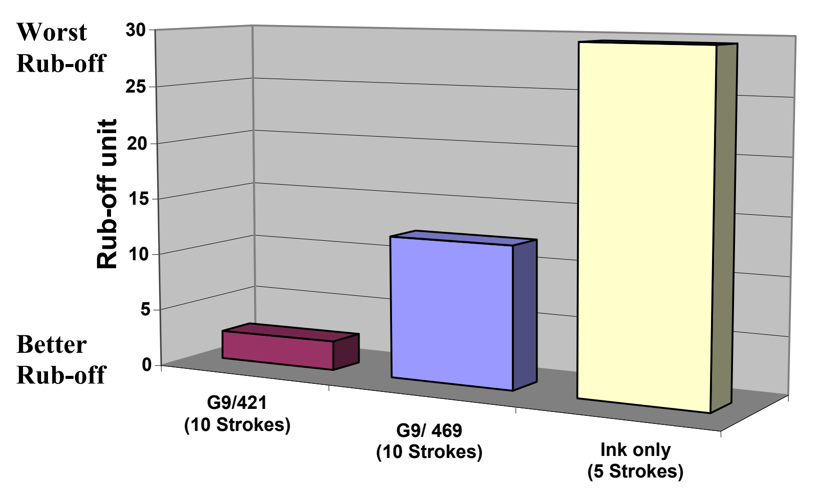

Figure 8.11: The relationship between the number of strokes and wet rub-resistance
For Casein water based ink with water based lacquers overprint

Figure 8.10 shows the dependence of dry rub-resistance of the printed sample with casein water base ink coated by varnish layer (water based lacquers G9/469 and G9 /421). The resistance for rubbing-off the ink film increases with the increase of the varnish film thickness from 4 µm to 24µm.
Figure 8.11 shows the important of over print with water based varnish to enhancing the wet rub-resistance of printed ink film.
From figures 8.10 and 8.11 it can be seen too, that the lacquer G9/421 is better than the lacquer G9/469 for increasing the dry and wet rub-resistance of the printed ink.

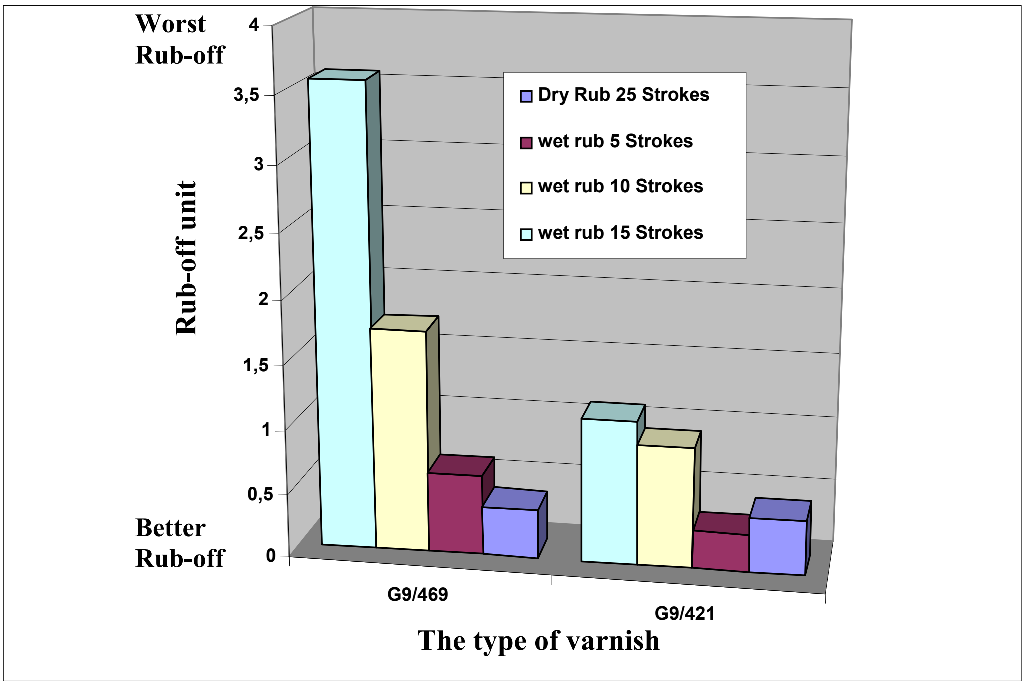

Figure 8.12: the relationship between the number of strokes and dry /wet rub-resistance
For Casein water based ink with water based lacquers overprint

Figure 8.12 shows the dependence of dry and wet rub-resistance on the varnish overprint -with a water based lacquers G9/469 and G9 421- on the printed samples with casein water based ink. It can be seen that the resistance for rubbing off the ink film decreases initially with the increase of the number of the strokes as seen from 5 strokes to 15 strokes.
From figure 8.12 it can be seen too that the lacquer G9/421 is better than the lacquer G9/469 in increasing the dry and wet rub-resistance of the printed ink.

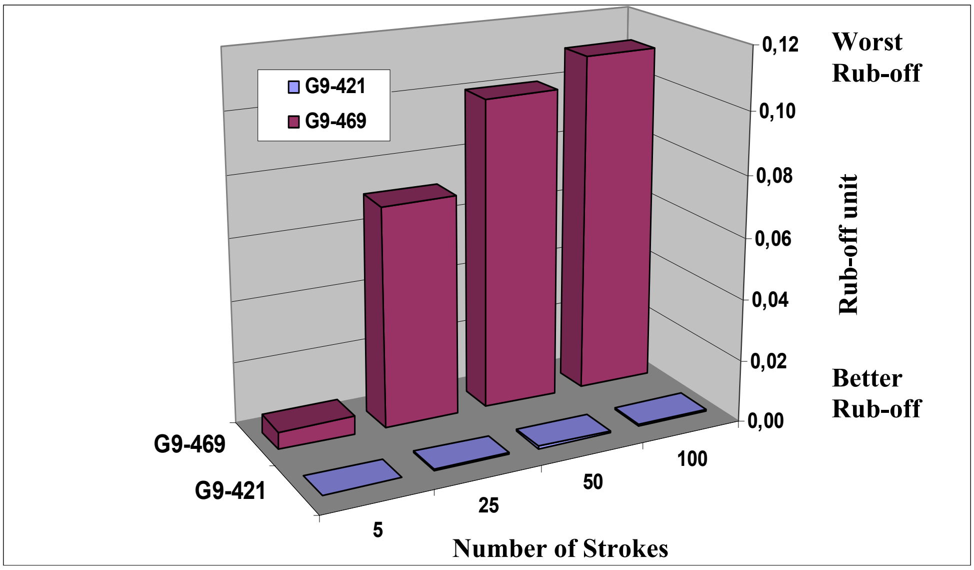

Figure 8.13: the relationship between the number of strokes and dry rub-resistance
For Casein water based ink with water based lacquers overprint

Figure 8.13 shows the dependence of dry rub-resistance on the varnish overprint -with a water based lacquer G9 421 and G9 469- on the printed samples with casein water based ink.
It was found out that the rubbing-off of the dried printed ink film is excellent by using a lacquer G9 421 over print as shown in figure 8.13.Also, by use of the lacquer G9/469 the resistance of rubbing-off of the dried printed ink film decreases initially with the increase of the number of strokes from 5 to 100 strokes.

Chapter 9

Measuring the change of paper dimensions after printing with Water -based Ink

9.1 Introduction

As mentioned in previous chapters, there is an increased trend towards the use of water based inks instead of solvent based inks with the aim of reducing the environmental impact of the printing inks.

In addition, a successful test was done for combined microwave-air convection drying method by keeping the substrate at room temperature. The dryness of water based ink was occurred without any negative thermal effects on the paper itself in un-printing areas. Furthermore, a water-based overprint lacquer has improved the rubbing-off of casein ink film.

The main aim of this chapter is to measure the dynamic elongation of the paper substrate after printing with water-based inks (casein ink). These measurements are very important to examine the possibility of drying the ink by the microwave dryer before the relevant dimension changes occur. This is significant to avoid registration errors and other problems which generate loss of quality in the multi-color printing process with water based inks.

To accomplish that, a device was designed and built to measure this dynamic elongation of the paper after printing with water based inks. By such device, different amounts of ink on the paper and viscosities were tested.

From reports of industrial printers using water based inks and from our printing run measurements it was evident that the dynamic of the dimension changes of the same paper after printing with water based inks and pure water are quite different.

In principle it may be assumed that the dynamic elongation may depend as well from the viscosity of the ink as from the amount of the water in the ink film.

9.2 Measurement of the dynamic elongation of paper after printing with water based ink

The experiences from production presses show that the transversal dimension changes would be in order of 2 to 3.7 % [120] and need a time up to seconds. No more information in detail was available about the dimension changes of the paper after printed it with water based ink. Therefore, a special measuring device as shown in figure 9.1 was designed and build-up to study the dimension change of paper as function of the time. In this measuring device, the paper samples were printed in a very short time with different

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[120] Richard E. Mark & Koji Murakami, Handbook of physical and mechanical testing of paper and paperboard, volume 2, Marcel Dekker, INC, New York, 1984, P.425.

viscosities of water based ink and also with pure water in order to investigate the change of dimension after printing. The details of measurement procedures are like listed below:

a. The printing unit: the coating was done with a printing cylinder rolled on the strip of paper (260 mm×85 mm ±0.5 mm) from a flat-bed inking system. To avoid a coupling between the printing process and the measurement the printing cylinder rolls transversally over the paper strip. The paper strip was placed on a rubber blanket. The ink film was brought on to the paper in less than 0.14 s. It was possible to produce solid prints with different amounts of ink on the paper, up to ink films of 18 g/ m².
To avoid evaporation of water from the ink, the inking unit was cooled at a temperature under the dew point.

b. The measurement of the dimensions changes: for this aim a metallic bar was used which flections changed with the elongation of the strip; obtaining an electrical signal to the elongation by means of a strain gauges bridge on the bar and a bridge amplifier. The final elongation was read from a mechanical displacement gauge.

c. The record of the dimensions changes as function of the time: A two channel digital oscilloscope with a hard copy printer was used. The measurements were triggered by the signal of a ceramic piezoelectric sensor placed under the blanket of the printing unit.

d. The measurement of the amount of water in printed or un-printed paper was determined through weighing the paper and the print before and after drying in an oven at 105 °C for a period of 30 min[121].

9.3 Materials

As in previous chapters, the measurements were done for 70 g/ m² papers having (4 - 4.5 %) moisture content in the paper, casein water based ink with a production kinematic viscosity corresponding to 24 s (Frikmar flow cup, 4 mm nozzle diameter, at room-temperature) was used. The amount of water in the ink is about 60 % of the total ink constitutes.

9.4 Measurements

It was possible to begin with the measurements, after a successful test of the new device (figure 9.1) to confirm its ability for measuring the dynamic elongation of paper immediately after printing. The aim of the measurements is to find out, how the dynamic

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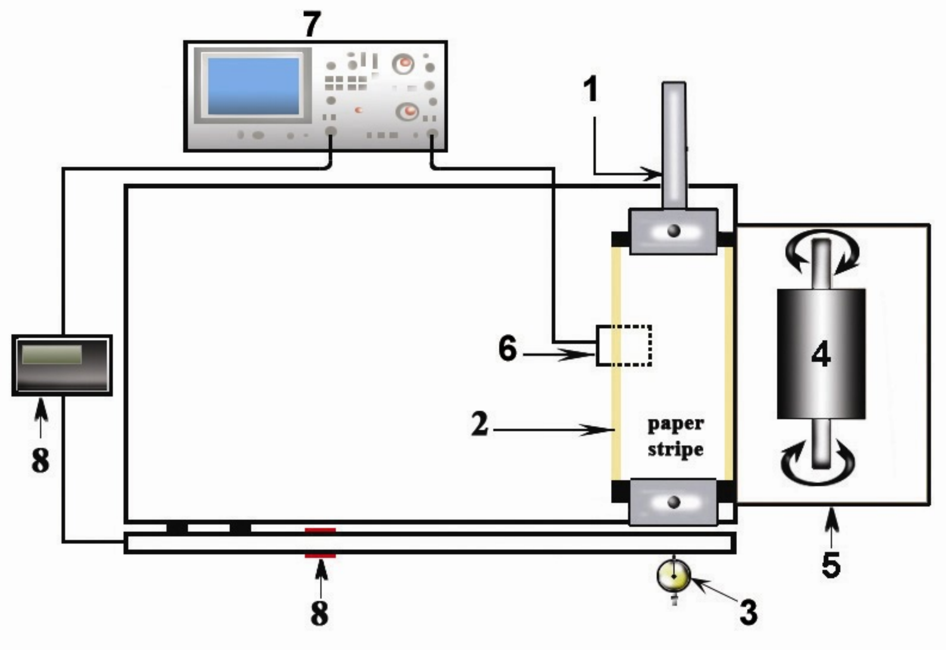
[121] Deutsches Institute für Normung e.V., DIN EN 20287-Die übersetzung der international Norm ISO 287, papier und pape Bestimmung des feuchtegehaltes wärmeschranksverfahren, sep. 1994.

elongation changes as a function of both, the viscosity of the ink and the ink film thickness. Therefore the measurement plan included:

- Elongation measurements for water based ink with viscosities corresponding up 10.5 s to 24 s (Frikmar flow cup, 4 mm nozzle diameter, at room-temperature).
- For comparison, the elongation measurements were also made with water instead of ink

At each condition a larger amount of measurements to get statistical relevant results were conducted. The measurements were done in an acclimatized room with rh = 45 % to 60 % and t = 21 °C to 23 °C[122].



(1) Screw to set up the paper strip tension (2) rubber blanket
(3) Mechanical displacement reader (4) Inking roller (5) Inking plate
(6) Piezoelectric sensor (7) Digital storage oscilloscope
(8) Strain gauges bridge on the bar and a bridge amplifier

Figure 9.1: Structure of the device to measure the paper elongation after printing with water based inks

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[122] Deutsches Institute für Normung , DIN 50014 -1985-07.

9.5 Results

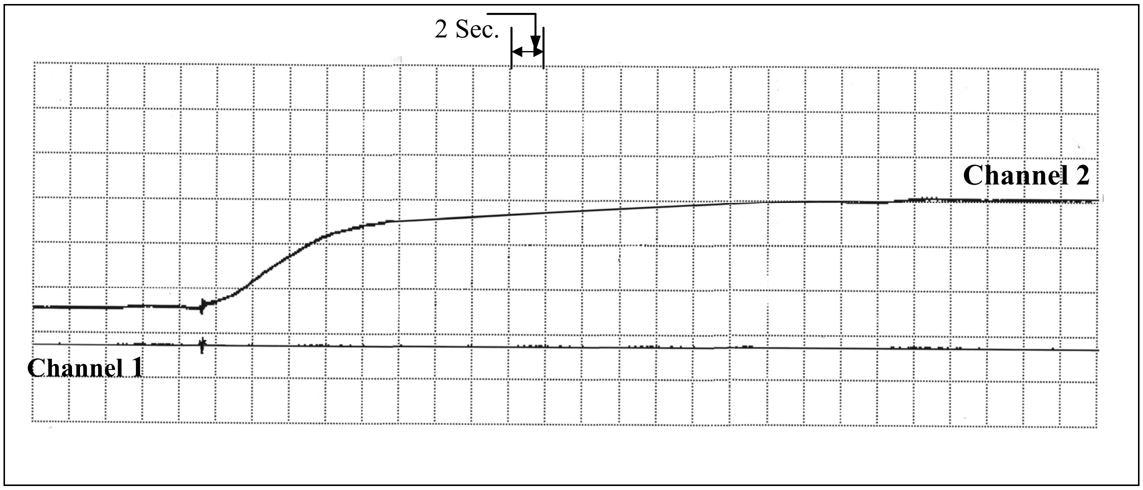
From the conducted measurements, it can be seen that the final elongation is - as expected - in a first approximation proportional to the total amount of water in the ink on the paper. This elongation is as expected much larger in transversal as in longitudinal direction[123] which is already well known.

About the elongation as a function of the time: The paper elongation **x** after being printed went asymptotically to a final value $\mathbf{x_0}$**,** without dead time after the printing; either there is no dead time or the dead time is below the resolution of our device. It was assumed for the change of dimensions in the time **t** an exponential behavior as follows:

$$\mathbf{X = X_0 \left(1 - e^{\frac{-t}{t_0}} \right)} \qquad [9.1]$$

Where: $\mathbf{t_0}$ is a relaxation time.

Figure 9.2 shows one example of a measurement of the enlargement after printing as a function of the time. From such measurements it is possible to obtain the value of the relaxation time.



Channel 1 is signal of a ceramic piezoelectric sensor to record the time.
Channel 2 is electrical signal to record the elongation by means of a strain gauges bridge on the bar and a bridge amplifier.

Figure 9.2: the elongation of paper after printing as a function of the time

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[123] FOGRA, Beziehungen zwischen ausgewählten Eigenschaften von Druckpapieren und ihrem Umgebungsklima, H.L. Bumgarten und K.Wurster, 1984.

Figure 9.3 shows the relaxation time as function of the amount of water which is applied on to the paper with ink in six viscosities and also for water.
It is evident that:

- There is no or a very short dead time
- The dynamic of dimension changes after printing, characterized over the value of the relaxation time $\mathbf{t_0}$ as in equation (1) shows quite different behaviours depending on the viscosity.

Surprising result is that the relaxation time $\mathbf{t_0}$ changes with the total amount of water, but the gradient depends on the viscosity.

As seen in figure 9.3 the relaxation time $\mathbf{t_0}$ is much longer than the remaining time of the printed web in the microwave dryer. Therefore the microwave dryer for water based ink is quite relevant to the initial speed of dimensions change of the paper.

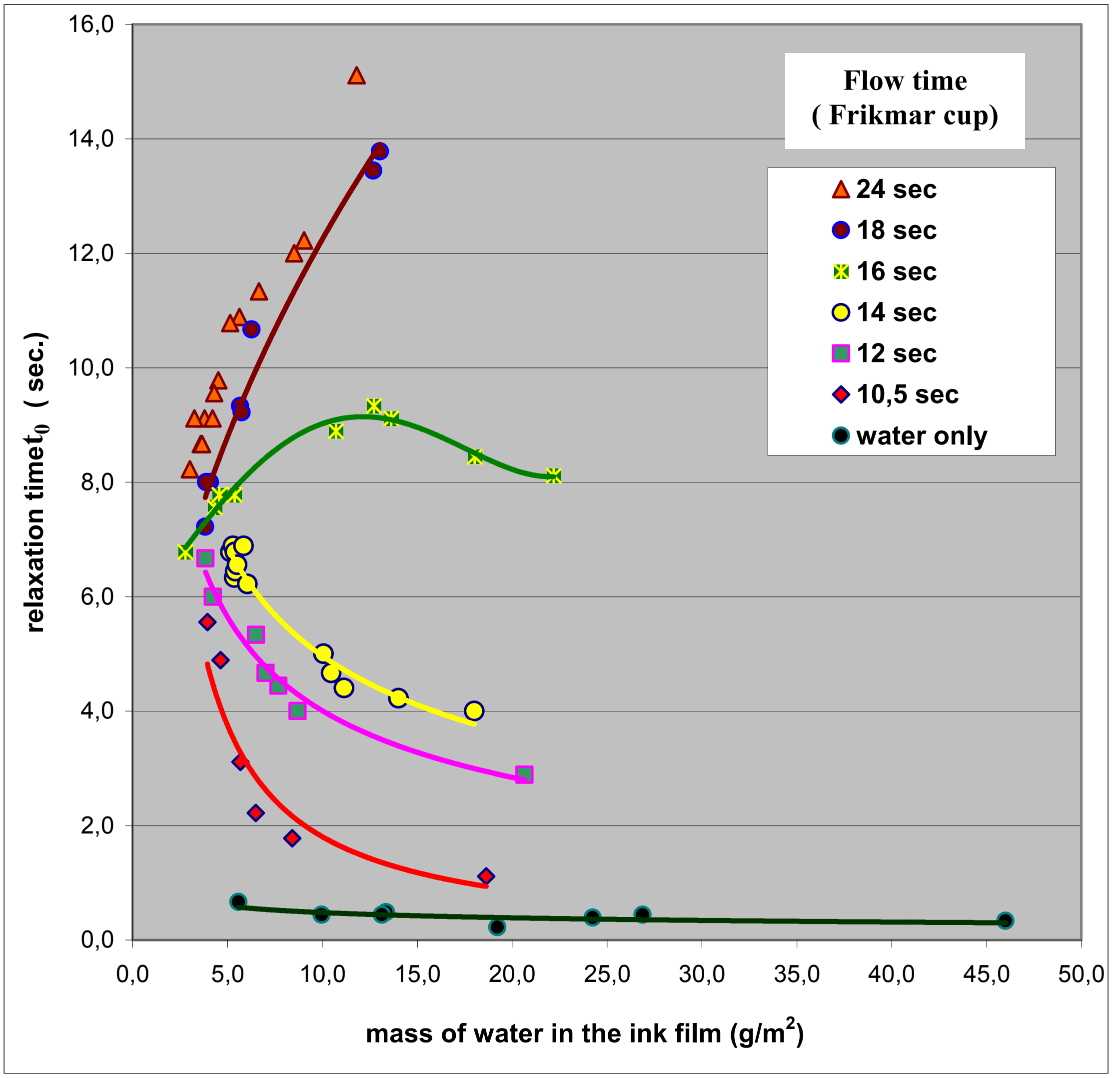

Figure 9.3: The relation between the mass of water in the ink versus the relaxation time

Figure 9.4 shows this speed as a function of the amount of water applied with the different ink film thicknesses onto the substrate and of the viscosities.

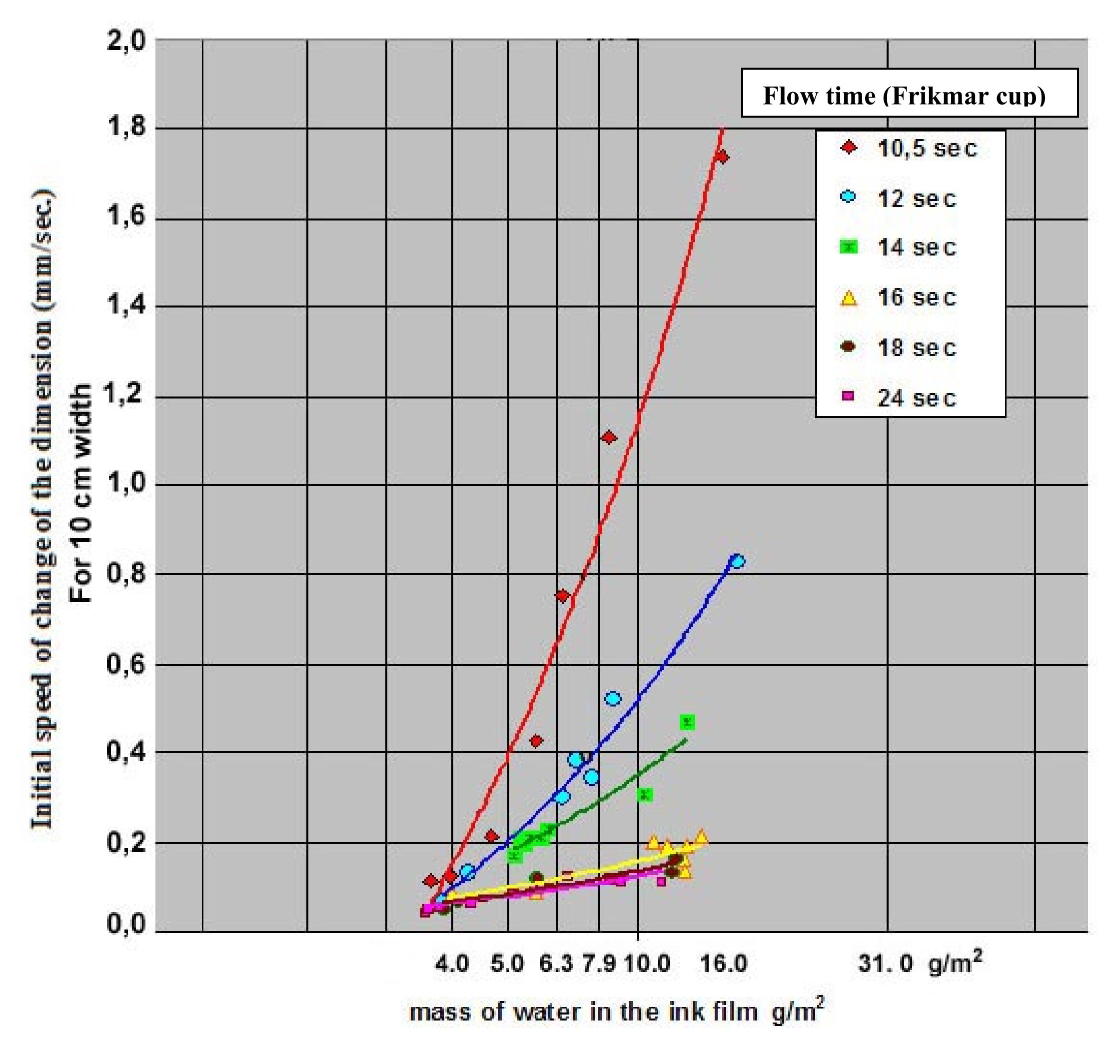

Figure 9.4: The initial speed of the dimension changes as a function of the amount of water in the ink and of the viscosity

Chapter 10

Conclusions and proposal of gravure press with a new microwave dryer and lacquer unit

The main objective of this study was to reduce the environmental impacts of printing inks especially in the packaging printing. As already discussed, in the packaging printing mostly solvents based inks are used in which VOCs are up to 70% of liquid ink.

These VOCs would be released partially or totally to the atmosphere in exhaust system and some percent of it retained from the ink on the package which make negative effects in aroma and taste of the food inside the package.

Therefore, a free VOCs water based ink instead of solvent based ink was tested to reduce such environmental impacts. To use this ink, some technical problems related to the drying and printing quality should be solved. This includes the weak resistance against rubbing-off and water, as well as difficulties related with the elongation of paper. Those problems can be overcome with microwave drying as proved to be as a reliable technique able to speed-up the drying time of the printed ink film faster than any relevant dimensions change. The rub-resistance of those reversible drying inks was improved by using a lacquer as well.

10.1 Conclusion and resume of the results

The drying of water based inks with the aid of microwave fields is an interesting alternative as it evaporates very efficiently the water from the ink without a strong drying or heating up of the substrate. It has been found that:

a. The microwave drying, and therefore the applicators must combine the irradiation with microwave energy with an effective air convection to transport away the water vapor and to keep the substrate at a low temperature.

b. The drying effects increase exponentially with the amount of water: it evaporates very well the water from thick ink films; the losses of moisture of paper substrates are absolutely and comparatively lower on light papers.

c. As a consequence of b., the microwave drying is advantageous especially for the initial drying and the microwave stage should be followed by warmed air convection dryer to complete the drying process.

d. As a consequence of the point b., and c., the microwave drying is advantageous specially for the drying of thick ink films on light weight papers.

e. As another consequence of the point b, the microwave drying leads to equalization of the amounts of water on the substrate.
f. It is possible to evaporate the water of the ink before a relevant dimensions change takes place.
g. Water based inks without VOCs as those with casein as binder are considered reversible drying inks, this means the dried ink film can be dissolved by water or aqueous liquids. This problem can be solved by applying an over print with water based lacquer on the printed surface.

These results are new and could be applied in the printing industry together with microwave drying as a new way for the application of water based inks.

10.2: Proposal of gravure press with a new microwave dryer and lacquer unit

The proposed gravure printing machine as mentioned in figure 10.1 comprises as in standard packaging presses a web in-feed (1), several printing units (2) and a rewinding device (6). The difference between this proposed gravure press and the usual gravure presses are:

1. Every printing unit has a microwave dryer followed by an usual warm air dryer.
2. A lacquer unit is located after the last printing unit.

The evaporated water can be released directly to the outside air (3) without any environmental problems. The lacquer unit (4) with water based lacquer located after the printing and drying units, this water-based lacquer has a little amount of ammonia which is released while drying the lacquer irreversibly. As a lacquer must only be wet, without having other printability properties, a limited amount of ammonia may be enough. Ammonia is a simple and cheap chemical element which can be separated easily from the exhaust in a washer and then fixed (5). Paper as substrate is suitable choice because:

- it was shown that , the dimensions change after printing with water based inks may be avoided by using of the microwave dryer,
- another water based lacquer may be applied on the internal side of the paper depending on the products to be packaged.
- Paper is composed mainly by cellulose fibers, a renewable raw product.

10.2.1 Environmental relevance

In Germany the emissions of VOCs from the gravure printing is about 10 000 tons/year, the emission from gravure packaging printing represent about 65 % from the total amount of these emissions[124].

From the ink technologies and market requirements in different branches of gravure printing it can be described like:

1. In the "gravure décor printing" water based inks are used since about 1990[125], but today it has still technical problems in the field of drying which is not completely solved.

2. In the "gravure packaging printing" both the customers and printers are interested to print with water based inks. The customers desire to print their packaging materials with water based inks to avoid the odour from the retained solvent which causes negative effects of aroma and taste of packed goods.
   The printers also want to use water based ink to reduce the VOCs emissions. But some technical problems especially drying make it very difficult to shift for using water based inks.

3. The field of "publication gravure printing" has no interest to print with water based inks, as the result of the successfully use of solvent based inks (Toluene as solvent) with environmental handling technologies. The solvent can be successfully recovered from the exhaust air. Furthermore, there is no stress from the customers to print without odour from the inks as in packaging printing.

Therefore, a strategy to reduce the environmental pollution from gravure printing to replace solvent inks with water based inks as alternative may look like:

1. The décor printing companies already use exactly the same reversible drying water based inks without any VOC-emission as proposed in this work. The microwave drying should be tested and developed to solve the drying problems and other technical problems.

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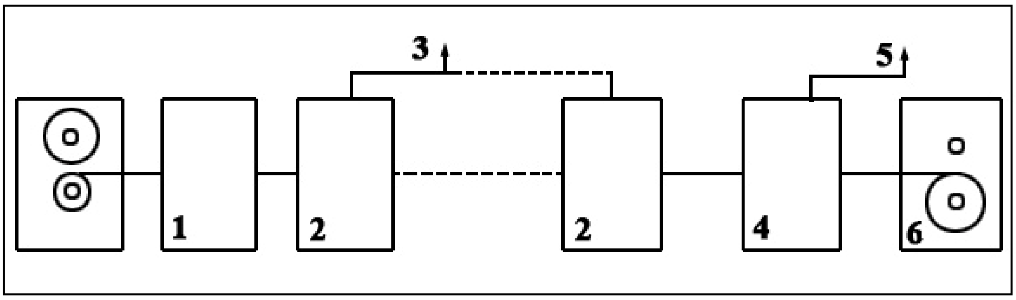
[124] C.Tebert, Lösemittelbilanz und Reduzierungsplan in der Druckindustrie, 2002.

[125] Private communication with Dr.David, Interprint, 08-2006.

2. After a solution of initial difficulties in décor printing it would be possible to introduce water based inks in packaging printing. As packaging printing produces 65% of the total amount of VOC-emissions in Germany, this would be reduced by using a VOC-free water based ink over printed with water based lacquer in order to reduce the environmental pollution. The proposed structure of the gravure press with microwave dryer can be applied in packaging printing as in figure 10.2.

3. If the new gravure press proves to be successful in the packaging printing, the gravure publishing printing would be the next step.



1- Web in-feed

2- Printing units

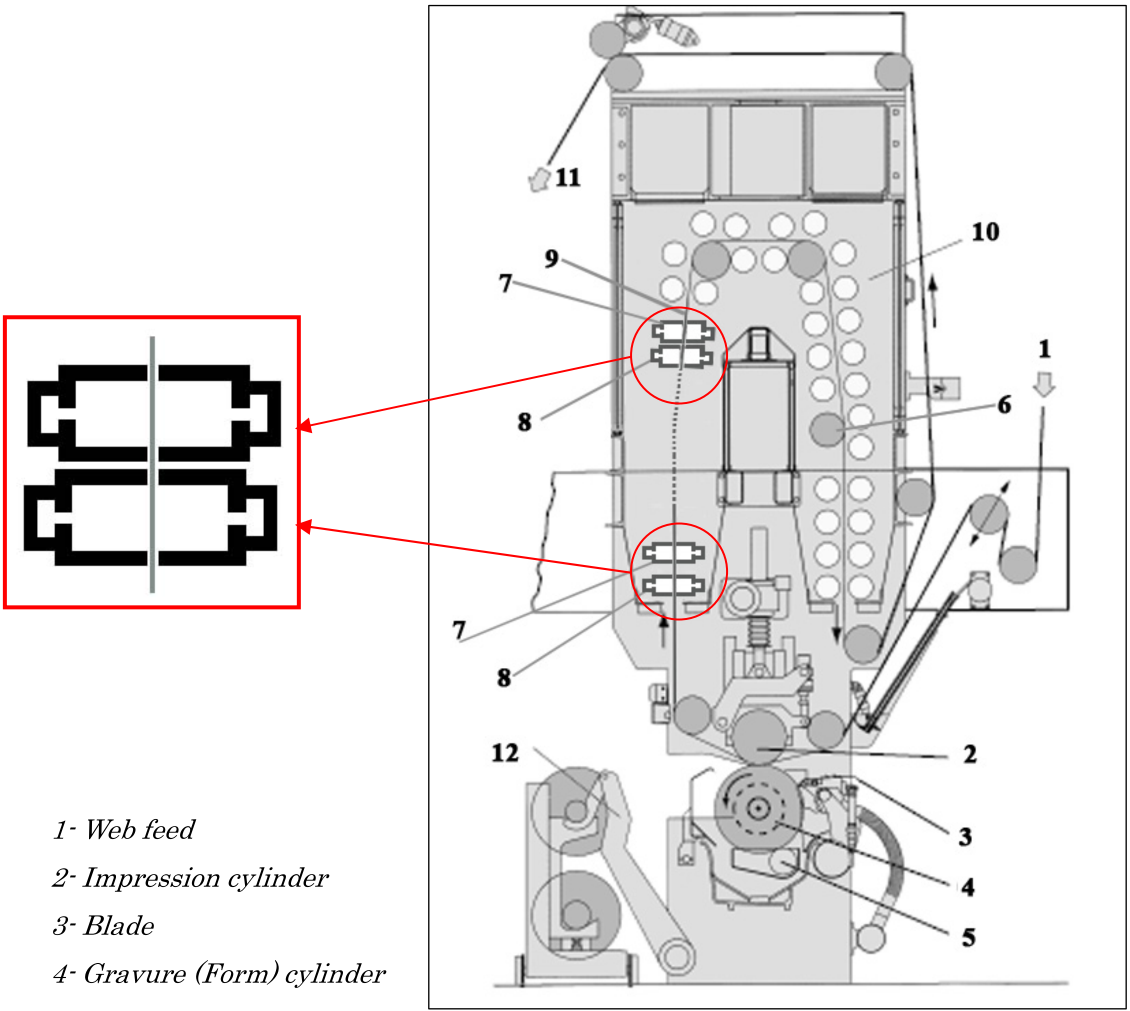
3- Dryer and exhaust directly to outside the press room

4- Lacquer unit

5- Dryer exhaust (NH_3-cleaning)

6- Web rewind

Figure 10.1: proposal of gravure press with microwave dryer to Print and laminate with water based ink and lacquer.



1- Web feed

2- Impression cylinder

3- Blade

4- Gravure (Form) cylinder

5- Inking unit

6- Web idler roller

7- Microwave dryer module with two waveguide resonators. The maxima of one resonator is on the minima of the other one and vice-versa.

8- Conducts for the air necessary for the convection in the waveguide resonators

9- End of microwave drying section

10- Warm air dryer

11- Web outlet

12- Device for changing the gravure cylinder

Figure 10.2: Microwave dryer in the printing units of the proposed gravure

Appendix

A. **Test a microwave dryer to be used in a narrow-web décor printing press**
B. **Contents of Figures**
C. **Contents of Tables**
D. **Abbreviations**
E. **References**

Appendix A:

Test of a microwave dryer to be used in a narrow-web décor printing press

Narrow web décor presses are used for prints of new decoration patterns. The web is 60 cm wide and the printing speed has up to 40m/min.
The microwave dryer for such a press was built by using the results of the present work.
The microwave dryer should be mounted as initial drying section between the printing unit and the conventional warm-air dryer.

The description of microwave dryer

The microwave dryer consists of two modules, each one with two microwave applicators; the applicators are operated in resonance and have a rectangular cross-section of 8.6×4.3 cm.
The power maxima of one resonator are on the minima of another to achieve a uniform drying of the ink film on the printed web.
The resonance operation is reached by using copper rods fixed in a minima position parallel to the electric field.

To measure the electric field strength inside the waveguide, a crystal detector[1] was used as said earlier in chapter 6 of this thesis.

Each waveguide resonator has two channels for convection drying air, an air impinging system to feed with an adequate air circulation against both side of the printed web (figure 2) to remove evaporated water from the ink and keep the temperature of the web through convection at nearly room temperature.

By blowing with warmed air and measuring the increase of the web temperature, it is possible to estimate the heat transfer coefficient of the convection drying. The result was about 60 ± 10 W/m² °C. This means a boundary layer thickness of about 0.43 mm, the amount of air blowed was 260 m^3/h.
Four magnetron heads (air-cooled) were used as sources of microwave power at power levels in excess of 3, 2 kW (4× 800 W) with frequency: 2. 45 GHz ± 50 MHz.

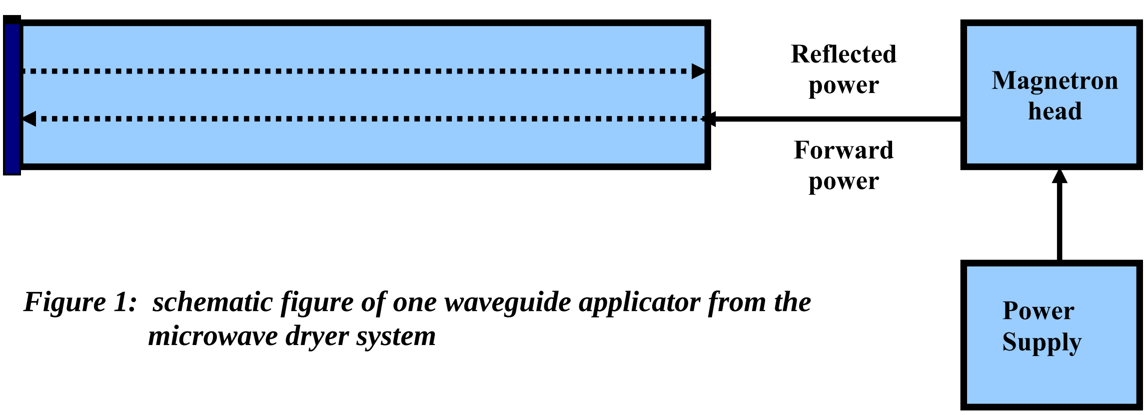


Figure 1: schematic figure of one waveguide applicator from the microwave dryer system

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[1] HP, Crystal Detector, Model 8472 A (NEG), USA.

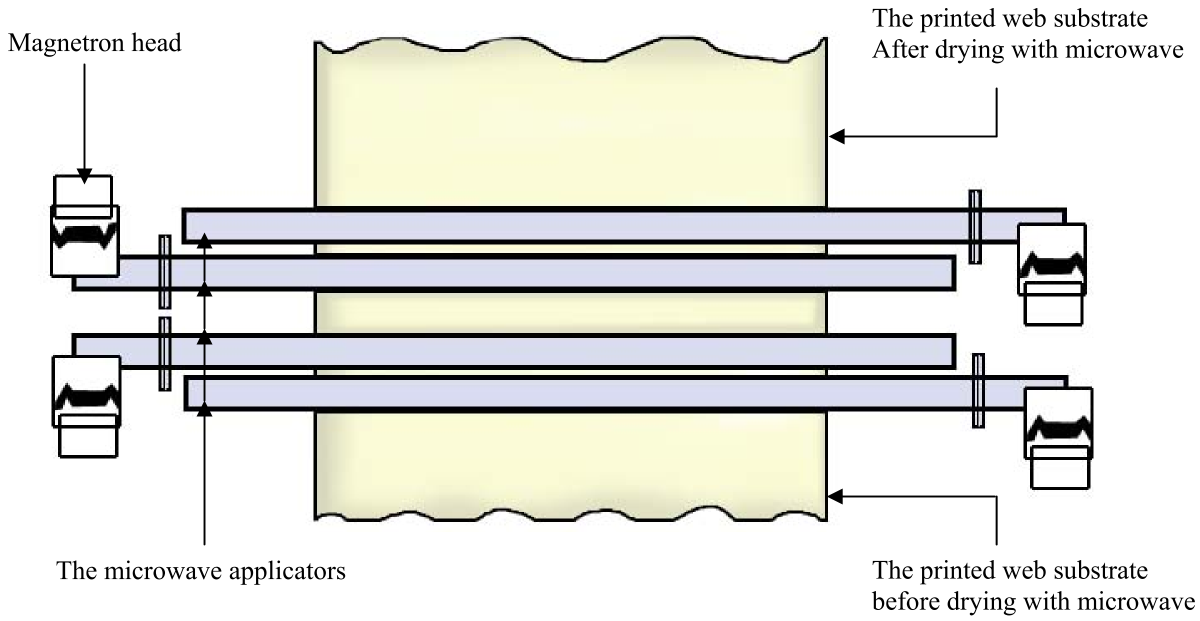

Figure 2: The microwave applicators, including slots for the printed web substrate

Measurement of the relative water losses from the printed ink film as a function of time for different ink film thicknesses by using microwave process dryer

As described in chapter 7, the same paper and ink were used to conduct the tests with this process microwave dryer. The printing speeds were from 10 m/min up to 30 m/min.

Results:

1- From the experimental works, it was found that the value of electric field strength for un-printed paper was about 2.8 times higher than for the printed paper with water based inks. This means that, it should be used a circulator device to protect the magnetron from the reflected power of the un-printed areas.

2- As earlier described, the modules with two applicators in resonance allowed a uniform drying of the printed web as expected.

3- In the earlier tests the air flow through the resonator leads to the web temperature was about 21 °C (room- temperature). But in these tests the web temperature after run off the microwave applicator was about 35°C, and it was found that there were no moisture losses at all from the un-printing areas.

4- From figure 3 it can be observed that, the drying time of an ink film thickness of 6.1 g/m2 (cell depth of engraving: 18 µm) is longer than in case of a film thickness of 4.4 g/m2 (cell depth of engraving: 12 µm). This means that the power of the microwave sources was not enough.

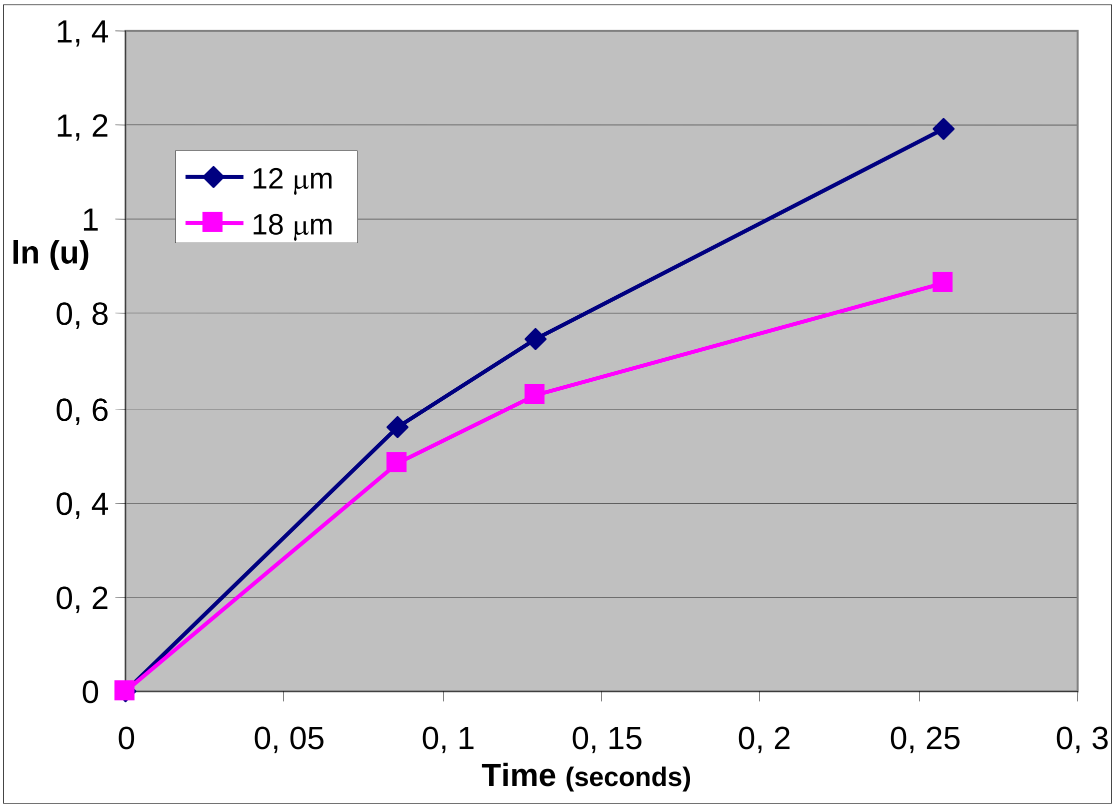

Figure 3: *the relationship between time and ln (u) with different ink thickness (cell depth of engraving named in diagram)*

Appendix B: List of Figures

Appendix C: List of Tables

Appendix D: Abbreviations

$\dot{Q}$: is the rate of heat transfer in (W/s)
α : is coefficient of heat transfer (W/m^2.K)
A : is area of dryer (the surface area of the ink will be dried) in m^2
$\dot{m}$: evaporation rate (mass of the liquid is transferred away from the printed Web) in (kg/h)
σ : mass transfer coefficient,
$P_{surface}$: saturated vapor pressure at the ink surface
P_{air} : pressure of air above ink layer
c : speed of light in free space (about 3.10^8 m/s)
f : frequency (Hz).
E_i : incident electric field
E_r : reflected electric field
v_p : plane phase velocity
λ_c : cut-off wavelength
α : attenuate in nepers per meter
δ_p : power penetration depth
ε' : relative dielectric constant for the material
Z : relaxation time
η_v : viscosity of the ink film
P : microwave power absorbed in the little volume element V
E_i : the internal (in the ink film) electric field strength
f : the frequency in hertz
ε_0 : relative permittivity of the vacuum
ε'' : loss factor of the dielectric ($\varepsilon' \tan\delta$)
m_w : the change of the mass of water in printed ink film
r : specific heat of the water
P : forward power in (kW)
$a.b$: cross section of the waveguide in centimetres
λ_g : waveguide wavelength in centimetres
λ_0 : wavelength of free space in centimetres
μ_0 : Permeability of free space
ε_0 : Permittivity of free space
v : printing speed in (m/min)
b : narrow side of waveguide in (cm)
t : remaining time in the waveguide in (s)
m_{WF0} : Weight loss in the oven of printing areas without MW-drying
m_{WP} : Weight loss in the oven of un-printed paper,
m_{WF} : Weight loss in the oven of printing areas with MW-drying
τ : characteristic drying time
m_{before} : weight of the printed sample before drying treatment
m_{after} : weight of the printed sample after drying treatment
m_{Alu} : weight of the aluminium foil piece to wraps the printed sample
t_0 : relaxation time of dynamic elongation of the paper after printing with water based inks

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