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The drying of materials of all kinds is one of the oldest technical problems of mankind. For thousands of years, empirical experience was gathered, again forgotten and gathered anew. The first theoretic beginnings toward a solution of the drying problem came about in the middle of the last century-- at a time, therefore, when the foundation for our modern physics science was being laid. Drying problems are extremely complex problems. This is true also when the liquid we are dealing with is a simple one. They seem all the more difficult when we are dealing with the drying of complex mixtures as is the case with printing ink which is made up of several varied materials and must be imprinted on another material. A total theoretical understanding of the drying process even today is possible only in special, rather simple cases. In order to get out of this difficult situation, we must ask ourselves whether we may draw useful conclusions concerning the difficult case of interest to us when considering these calculable cases.

An experiment carried out by us mentally, is to help us in this. Let us imagine a water puddle of definite size and thickness of layer, which is to be dried up, that is to say, evaporated. In order to accomplish this, we use as a drying apparatus simply a closed drying room as the housewife uses if she wants to dry her wash in rainy weather. In our first experiment we leave our water puddle to the natural conditions of the room.

In a second experiment the same type of water puddle is heated to a higher temperature by means of some kind of heating apparatus and evaporated in the same type of drying room. We then note the time it takes in both cases to evaporate the water puddle. Our experience will tell us right away that the heated water puddle will dry up faster than the unheated one. We then repeat these experiments with a wet print, whereby we assume that an ink drying by the evaporation of solvents, namely a rotogravure ink or a Heat-Set ink is being used. Here, too, we will see that an increase in temperature leads to an increase in drying rate, therefore to a similar change.

We can imagine a whole series of such comparative experiments which all lead to the same results. They all confirm the fact that regardless of the type of liquid used, respectively, of the material mixture used, a change in the drying apparatus or a change in the drying conditions always leads to a similar change in the drying rate.

Owing to this fact, which, scientifically speaking, corresponds to the theory of similarity, we are in a position to apply theoretical knowledge gained by studying various drying systems presupposing the use of simple liquids to printing inks also.

If we further evaluate the imagined experiments and examine for instance, whether by making a change in the drying apparatus the percentage of increased drying speed in a simple liquid and in the drying of printing ink is the same, we will find that this is only approximately true.

This is so because here the basic difference in the materials to be dried shows its effect. In one case we were dealing with water, a pure liquid, in the other, we were dealing with a complex mixture consisting of pigments, resins, waxes and solvents and - as far as absorption is concerned - also encompassing the material to be imprinted. We, therefore, can only apply our knowledge qualitatively in a direct way and not quantitatively. Thus we are hitherto not able to figure out a purely mathematical explanation of a dryer for a printing press based on the drying theory. This realization is certainly not very satisfactory. However, we might say that it is not discouraging. The road of comparative experiments and comparative calculations also leads to our goal, although it is a much more tedious proceeding.

A first formulation toward a drying theory was published in 1855 by the physicist Fick. He started out with the assumption of a simple liquid, therefore, water for example, the surface of which is subjected to the influence of static air (Illustration 1). Basis of the mathematical formula is the fact that individual liquid molecules always succeed in leaving the liquid bond and are able to enter the static air. Thus a vapor layer is formed on the surface which reaches a concentration dependent on the surface temperature. The farther we get away from the surface, the smaller is the concentration of liquid molecules in the air. Fick has found the following connection for the drying rate--thus for the evaporating liquid weight per time unit:

$$G_D = -D \cdot F \cdot \frac{dc}{dl} \qquad (1)$$

(The negative sign is necessary since $\frac{dc}{dl}$ in the case of drying is negative. The drying rate, however, should be represented by a positive magnitude).

In Fick's equation the following applies:

D = Diffusivity [m^2/h]. This number is dependent on the type of liquid evaporated and on the temperature. It is a measure for the rate with which vapor molecules mix with the air.

C = Concentration of the liquid vapor in the air [kg/m^3].

l = A stretch of way in the direction of the diffusion current [m].

$\frac{dc}{dl}$ = Change of concentration in the direction of the diffusion current emanating from the wet surface

F = Free surface of the evaporating liquid [m^2]

This equation is based on the fact that two gases (respectively, two vapors, respectively, gases and vapors) always tend to mix and continue to do so until the mixture is statistically equal. A concentration difference between two points, therefore, always leads to a diffusion current in the direction of the higher to the lower concentration. The concentration gradient here appears as the driving force of the evaporation process.

Stefan published this same principle in 1871 in a somewhat different form as follows:

$$G_D = -\frac{D\cdot F}{R_D\,T_D}\cdot\frac{P}{P-P_D}\cdot\frac{dP_D}{dl} \qquad (2)$$

Here the driving force is the change of the partial pressure in the direction of the diffusion current.

Stefan's equation after a mathematical conversion may be approximately simplified:

$$G_D = \frac{D\,F}{R_D\,T_D}\,\frac{P_{D_O}-P_{D_L}}{l} = \frac{\beta F}{R_D\cdot T_D}\,(P_{D_O}-P_{D_L}) \qquad (3)$$

The following applies:

R_D = Gas constant of the solvent vapor [m kp/kg °K]
T_D = Medium temperature in the diffusion layer [°K = 273° + °C]
P_{D_O} = Partial pressure of the evaporating solvent on the liquid surface [$\mathrm{kp/m^2}$]
P_{D_L} = Partial pressure of the solvent vapor in the air [$\mathrm{kp/m^2}$]
l = Distance from the surface, in which P_{D_L} is measured [m]

In the second formulation of the equation (3) we find a new magnitude, namely the mass transfer coefficient $\beta = \frac{D}{l}$, which we will also encounter later on. The individual magnitudes in this formula are not simple constants. The partial pressures P_{D_O} and P_{D_L}, but also β, are dependent on the temperature of the liquid surface. Only the free surface F and the gas constant R_D are to be considered constants. The drying rate is, therefore, dependent on the temperature. We will remember this fact from our imaginary experiment. If we for example evaluate Stefan's equation for the solvent Toluene, we get-- if we write $P_{D_L} = 0$, that is presupposed a large enough drying Room - the course depicted in illustration 2 for the drying rate. A circle aera of D = 2m was assumed as free surface. As expected, the drying rate rises greatly with the surface temperature.

Sofar we have presupposed practically static air in our considerations. That is, we have considered conditions which approximately prevail when we place a wet print on a more or less warming surface for drying. This, however, does not represent normal circumstances, since in almost all cases the air is in motion during the drying process. Let us consider the processes during web-fed rotary press printing. The printed web to be sure, runs with cylinder circumferential speed through more or less static air; however, if we consider a surface element of the web that runs along we will observe an air motion on the surface, the speed of which is equal and opposed to the web speed.

We, therefore, must under all circumstances examine if and how the air motion influences the drying rate. Every housewife will be able to confirm for us that such an influence may be expected, since she knows very well that her wash dries much faster if there is a strong wind.

In order to be able to arrive at the speed influence, we necessarily have to take into consideration aerodynamic aspects as well as thermodynamic ones. Basis for these considerations is the theory of boundary layer, a branch of science which has developed only with the coming of aeronautics and which deals with the processes taking place in the immediate surroundings of a surface in an air flow. As it happens, the actual evaporation process takes places in that area, characterized by individual liquid molecules leaving the surface and entering into the air layer immedialety adjacent to the surface.

The application of the boundary layer theory to thermic processes in 1921 by E. Pohlhausen led to a first but only partially valid theory of heat transfer between flowing air and a surface. A few years prior to this, Nusselt had already recognized that the mass transfer which takes place on a liquid surface during an evaporation process obeys similar fundamental laws as the transfer of heat from a surface to the surrounding air. This fact was of decisive information to the development of the drying theory. It allows the direct application of information on heat transfer to mass transfer problems and thus to the drying process and conversely.

It is also interesting to note that among scientists O. Reynolds whose name we encounter daily nowadays when we talk of Reynolds number, seems to have been the first who recognized the influence of air motion on thermic processes, specially in heat transfer. A publication of 1874/75 points to this fact.

In the following I shall explain the interrelations for the very important case of the so-called forced turbulent flow without going into the very difficult derivatives. The starting concept is shown in illustration 3. Let us assume that an air flow with the velocity w_∞ flows alongside a pure liquid surface. The air molecules adjacent to the surface adhere to it so that the velocity there becomes zero. The area of declining velocity is defined as boundary layer. With the aid of the concept that as a result of the turbulent motion parts of the undisturbed current come into contact with the surface, there pick up vapor molecules which have left the liquid and again return into the current, it was possible to develop a formula for the drying rate. For the representation of the drying speed we use the one selected by Stefan, namely:

$$G_D = \frac{\beta \cdot F}{R_D \cdot T_D} (P_{D_0} - P_{D_L}) \qquad (3')$$

With the exception of the mass transfer coefficient ß there is no magnitude in this formula that can be directly dependent on the velocity. Therefore, we redefine the mass transfer coefficient and write the following:

$$\beta = Nu' \frac{D}{L} \tag{4}$$

whereby the following is valid:

Nu' = Nusselt number for mass transfer
This number includes all velocity dependents.

L = Characteristic length of arrangement

For our case we get:

$$Nu' = C \cdot Re^{m} \cdot Pr'^{n}$$

Whereby:

C = Constant, dependent on the geometric arrangement of the drying apparatus.

Re = Reynolds number $= \frac{w_{\infty} \cdot L}{\nu}$ = undisturbed velocity times characteristic length of arrangement divided by the kinematic viscosity of air-vapor mixture.

Pr' = Prandtl number for mass transfer $\frac{\nu}{D}$ = kinematic viscosity of the air-vapor mixture divided by the diffusivity.

m = Exponent, dependent on the type of flow; in the case of the turbulent flow $0,75 \angle m \angle 0,84$ is valid.

n = 0,34

We are above all interested now to learn how G_D is dependent on the velocity and also on the temperature. We, therefore, again write the complete equation for the drying rate and get:

$$G_D = C \cdot Re^m \cdot Pr'^n \; \frac{D}{L} \frac{F}{R_D \cdot T_D} \cdot (P_{D_0} - P_{D_L}) \qquad (6)$$

Of the magnitudes on the right side, only Re is dependent on velocity. Re, Pr', P_{D_0} and D are temperature dependent. Simultaneously we establish that P_{D_L} may be neglected, since on account of the low content of solvents in the drying air, its partial pressure will strive toward zero.

Based on known thermodynamic interrelations, each of the individual magnitudes of the drying speed equation may be put down as function of the velocity, respectively of the temperature. If we summarize the whole thing into a joint function, we get a new equation, namely:

$$G_D = K \cdot \frac{T^{Z1}}{e^{\left(\frac{Z2}{T}\right)}} \cdot w^m$$

A prerequisite for the evaluation of this equation is, of course, that we have exact knowledge of not only all material data of the solvent but also of the air flow. We then can exactly define Z1, Z2 and m and calculate the drying rate. Of course, at the moment neither the material data of all the solvents used in printing technology nor all the air flows possible are sufficiently known, so that a general evaluation is still not possible. For Toluene, however, which is used in rotogravure printing, and for a certain impinging air jet the evaluation may be carried out. Since other solvent-air flow combinations always act similarly, this evaluation is qualitatively of general validity.

The following illustration 4 represents the dependency of the drying rate on the average air velocity along the surface and the surface temperature. It allows us to arrive at three statements which are of decisive importance in the evaluation of drying systems:

1) At low air flow velocity and especially with static air, the drying rate is low even if the surface temperature is increased. In this area we find drying rates which correspond to illustration 2.
2) With rising air flow velocity drying rate increases considerably.
3) The rise of the drying rate is all the steeper, the higher the surface temperature chosen.

We are now in a position to compare drying systems with each other with regard to their operating efficiency.

First of all we have drying systems which operate without marked air flow. They always have a device which allows heating of the imprinted web to a desired temperature. In most cases a vapor hood is also present. This vapor hood permits the sucking off of the solvents that are free so that the ambient air is not adversely affected. Examples for such drying systems are the well-known heating drums which were originally customary in web-fed rotary gravure printing. Radiation dryers that operate with infra-red light or dark radiators and, of course, the micro-wave dryers belong in this group.

The air velocity of these drying systems is low and at the most is of a magnitude equal to the running speed of the paper web. Looking at illustration 4 we realize that the drying rate is low and that even a considerable increase in temperature would not make a high capacity system out of much installations.

It is well known that the surface temperature may not exceed the limits dictated by the printing procedure. First of all the evaporation tempefature of the solvent is the most important standard. This temperature should never be reached since the ink layer would necessarily be broken up by the formation of vapor bubbles. Much more limiting are the maximum temperatures existing for the solid components of printing ink or of the paper. These in all cases, lie far below the evaporation temperature of the solvents. In the rotogravure printing process for example, we may hardly exceed 50° C, whereas in offset and letterpress printing processes the maximum permissible temperature lies around 90° C.

Due to the limited drying capacity achieved thereby, attemps were made very early to provide the simple heating installations of the rotogravure presses with an additional air circulation system. The success achieved thereby was limited, since the importance of the current forms was not known. There are types of air flows with which no noticeable increase in air velocity can be achieved simply because there are retroactive effects on the paper web. This is true above all for those air flows which are exclusively conducted along the paper web, therefore, specially for the so-called parallel air flow. As a result of this unstable form of current, flutter of the paper web occurs which finally may lead to web breaks.

The so-called air-impingement dryers are more advantageous in this case. In these types of dryers, the air is blown out through individual nozzles vertically to the running web so that forces are created which are vertical to the paper web. In one-sided drying the paper web for example may be simply supported by guide rollers so that a stabile web may be achieved even at maximum air velocity. The problem is more difficult if both sides have to be dried simultaneously. Here not even the impinging air flow is stabile enough, so that reductions in the air velocity under certain circumstances must be accepted. For some time now, air flow types have become known which even in this case lead to a stabile paper web run. To what extent these correspond to the conditions for a high drying capacity must yet be made subject of thorough investigations.

I have to point out a second critical point now. The theoretical considerations which we talked about at the start are based on a speed w_∞ which in no way is equal to the exit velocity w_0 at the nozzles. The relationship $\frac{w_\infty}{w_0}$, which should be as great as possible is dependent on the width of nozzles, their distance to the paper web but also on the distance between nozzles. Two jet dryers which are of different construction may show great discrepancies in their drying capacity even if they both have the same velocity w_o at the nozzles. One may say roughly speaking that the better dryer shows a larger width of nozzles combined with a shorter distance to the paper web and a smaller distance between nozzles. The better one of the two dryers will, therefore, work with a much larger volume of air.

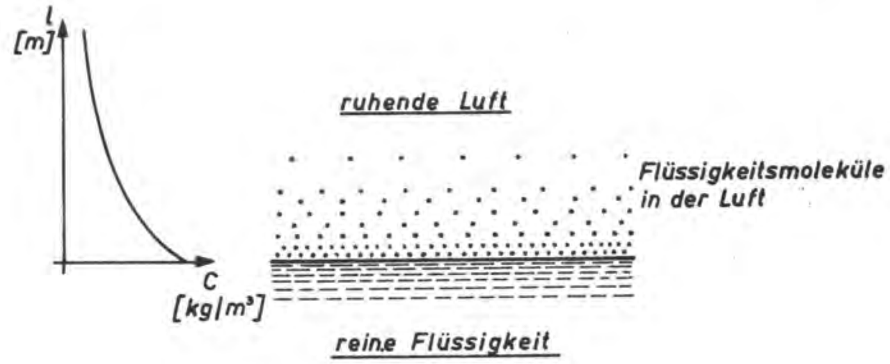
I would like to take up a third point, namely the question of heat supply. It is possible to provide heat independent of the drying air, for example by means of gas flames, radiation or microwaves. It is, however, also possible to use the drying air itself for this. This is particularly adventageous since in high capacity dryers high mass transfer numbers also correspond to high heat transfer numbers. Furthermore, the technical expenditure for heating the drying air is rather simple.

In arriving at these conclusions and considerations I was unable to take up many things, for example what is important to know if one decides to develop one's own dryer system. Above all this should include those processes that take place in the ink layer itself and which not only influence the drying speed but which also result in a reaction on the most favorable construction of a drying system with regard to temperature and velocity distfibution. I also purposely avoided to comment on the economy of individual drying systems. A mere consideration of energy balance which takes into account the fact that the creation of high air velocities of large air volumes is a comparatively expensive matter--the fan capacity rises with the second power of speed created and linear with the air volume--is actually not sufficient for the evaluation of economy. In any case, the overall efficiency of the rotary press and also the possible improvement of quality achieved with a dryer should be taken into account.

With my brief discourse on the drying theory I have tried to show that with regard to surface temperature of the material to be dried and with regard to the velocity of the drying air demands are made on an efficient drying system which cannot be neglected and I have attempted to give you evaluation criteria which make it possible for you to judge drying systems at least in principle.

FICK (1855)

Bild 1



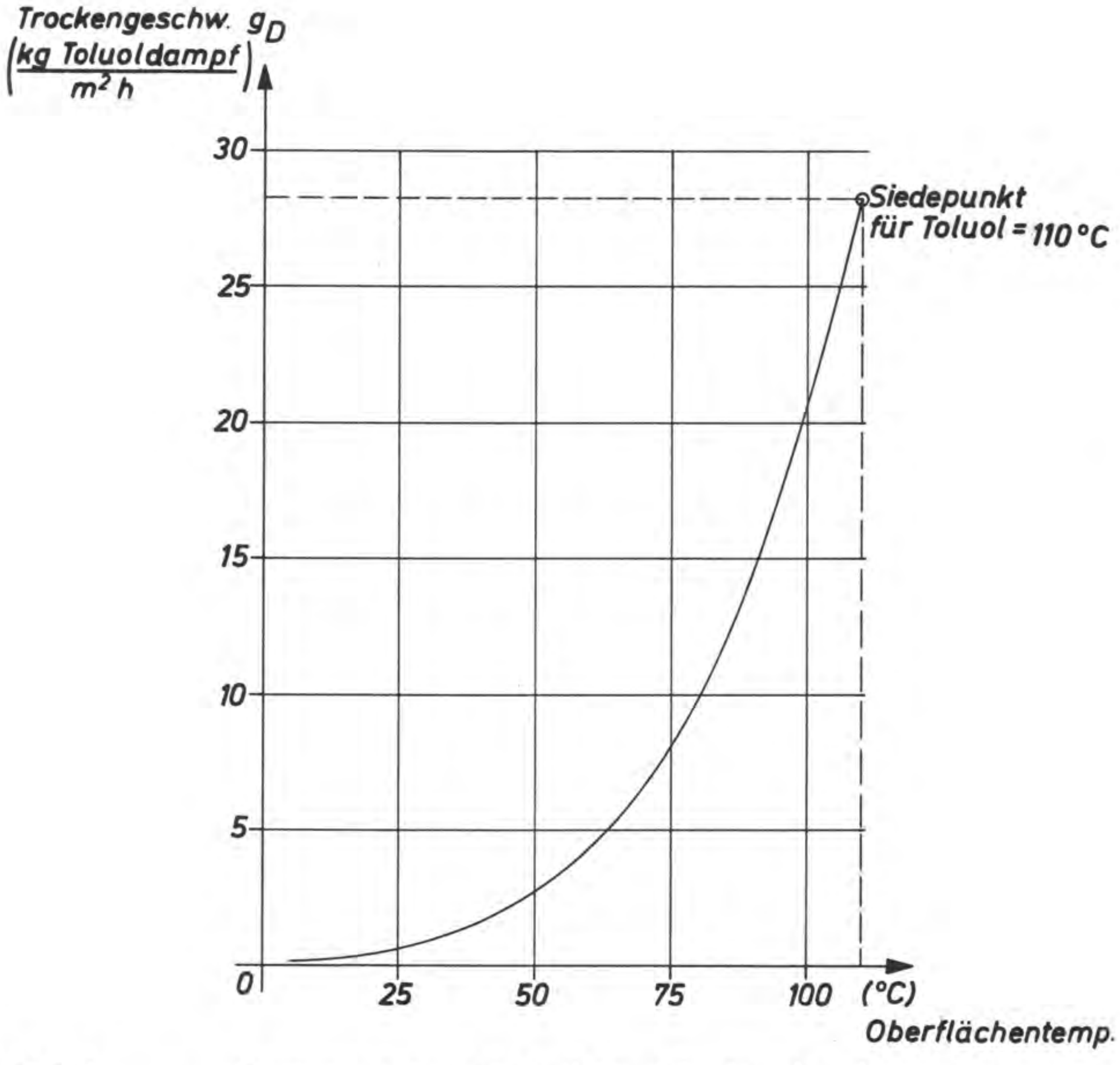


Bild 2 Trockengeschwindigkeit für Toluolverdunstung in Abhängigkeit von der Oberflächentemperatur in ruhender Luft für eine kreisförmige Trockenfläche mit D=2m.

Turbulente Strömung

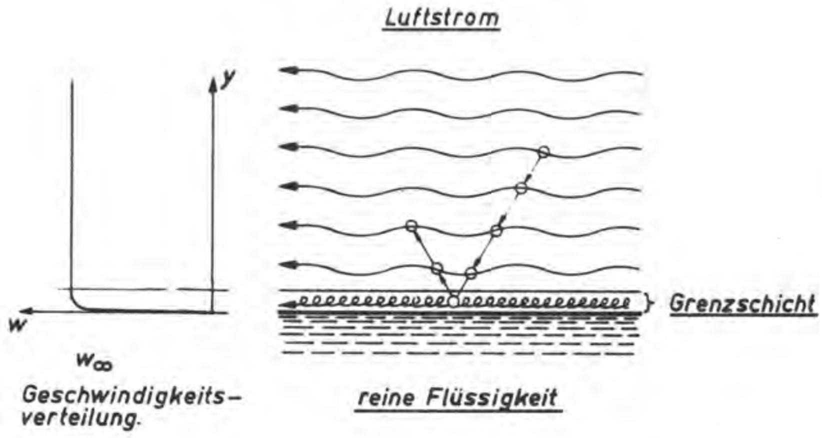


Bild 3

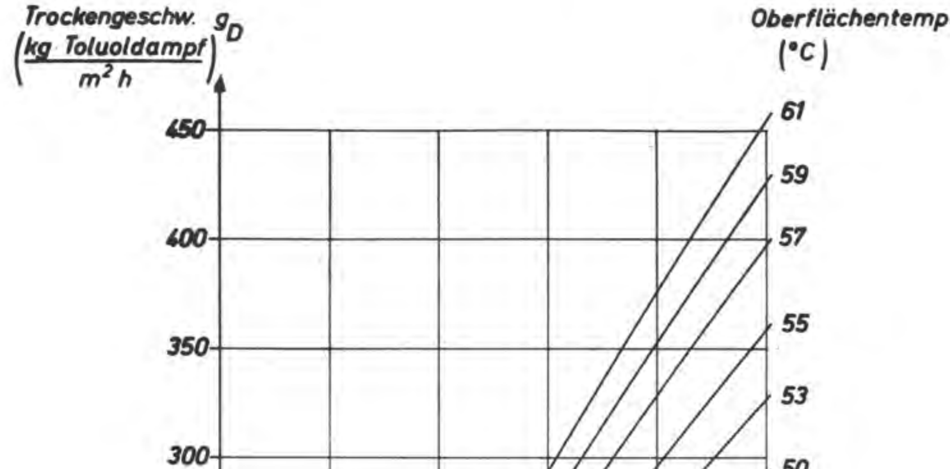


Bild 4

Maximal erreichbare Trockengeschwindigkeit für Toluolverdunstung in Abhängigkeit von der mittleren Luftgeschwindigkeit längs der Flüssigkeitsoberfläche mit der Oberflächen - temperatur als Parameter für eine kreisförmige Trockenfläche mit D=2m und eine runden Düse in senkrechter Anordnung.