Air-stream drying of paper

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Abstract:

Airflow drying has originally been applied in printmaking and hand papermaking workshops in order to shorten drying times and maintaining planarity of paper. The technique was already suggested by R. Futernick in 1988 and was first introduced to paper conservation at the Western Regional Paper Conservation Laboratory in San Francisco. In this contribution, the physical bascis of the drying process, including a simple drying stack prepared from corrugated board, are described. Drying is carried out in stacks of archival-quality corrugated cardboards and other paperboard materials under slight pressure. The stack of cardboards is equipped with a blower that provides a continuous airflow through the open channels of the cardboards. The water is removed from the stacks by continuous evaporation through the moisture absorbing board until equilibrium with the ambient air is reached.

Introduction:

Drying paper is one of the most important operations in paper conservation. Not taking into account the particular issues of drying after a flood disaster, a controlled drying always concludes controlled treatments that involve the application of liquids (usually water). Aqueous treatments include the humidification of paper in preparation of flattening, washing of paper for cleaning or deacidification, or their chemical stabilization if they are affected by iron gall ink corrosion. Basically, “drying” concerns the reduction of the physically bound water in the paper. This occurs by evaporation. Thereby, after wetting, the water content in the paper is reduced to a humidity equilibrium from approximately 18 % up to a maximum of 25 %, which is between 5 % and 9 % (depending on the type of paper) with respect to the paper’s dry weight. After an aqueous immersion, the water content of paper, at approximately 50 %, is significantly higher. That means that in the drying process, up to 40 % of the water must be removed from the fibres.

Drying method is key for restoring the mechanical strength properties of paper after an aqueous treatment. Further, the preservation of the integrity of the paper must be ensured by avoiding excessive tensions during the drying process that could damage the sheet. Finally, significant characteristics of paper such as its surface morphology and its dimensions can be decisively affected by the drying technique (Brecht 1958). Drying must therefore be considered a paper conservation step that significantly influences the treatment quality. Nevertheless, drying has only been given very little attention in the literature on conservation science and practice, except for the systematic analysis of drying aspects in the articles by Sugarman and Vitale (1992), Watkins (2002) and Mentjes (2006). A fundamental account of the principles of relevant drying techniques in paper conservation and their respective possibilities and limits has, however, not been realized yet.

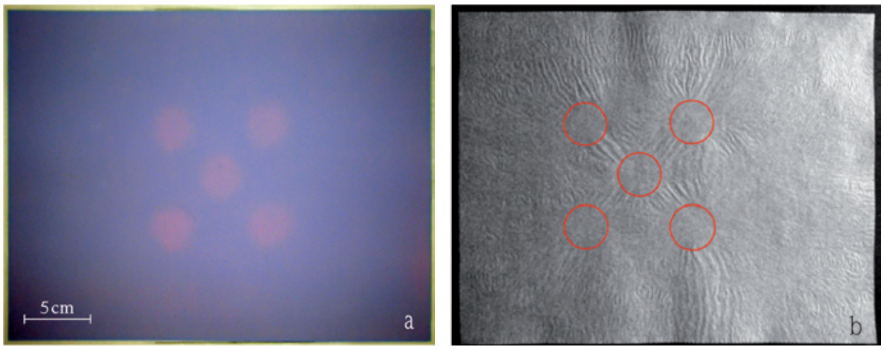


Fig. 1a and 1b

Drying in paper conservation:

The water content of paper stands in equilibrium with the relative humidity of the surrounding air at a given temperature and a given pressure. Under normal conditions (i. e. at a temperature of 23 °C and an atmospheric pressure of 760 Torr (=1 atm) and a relative humidity of 50 %), the equilibrium moisture content of paper is on average 6 %. Under these "normal" conditions, a damp piece of paper must give off water, in the form of water vapour, until it reaches its equilibrium moisture content. For this consideration, it is physically more correct to refer to the partial pressure of the water vapour in the atmosphere and the partial pressure of the water vapour in the pore system of the paper. A pressure gradient in one direction or another causes the paper and other cellulose-based materials to release water (drying) or absorb it (moistening), and establish a humidity equilibrium with the surrounding environment.

Quality treatment for the drying method:

All aqueous treatments involve changes to the characteristic structure of paper, since a majority of the hydrogen bonds in and between the fibres fixed in the material during paper manufacture are broken. The absorption of water results in a reduction of the paper stability and changes its dimensions and surface texture. The drying method significantly influences whether the paper returns to its original state and therefore determines the treatment quality. A "free" air-drying is roughly equivalent to hanging clothing out to dry on the line. Because of the inhomogeneous distribution of mass in the paper fibres, air-drying results in a non-uniform release of water that manifests itself in planar distortions (Brecht 1958). Planarity, one crucial requirement for paper drying, therefore cannot be met by air-drying. The uniformity of the drying process is key to avoiding drying irregularities that lead to distortions (*Fig. 1*).

Fig. 1a and 1b: Images of non-uniform dried paper, using the contact drying method (between blotters), on cobalt(II)-chloride indicator paper (a) and glassine paper (b): the cobalt(II)-chloride indicator paper remains damp longer in areas without any contact with the sorption-capable blotters (pink) than in the areas that do come in contact (blue), i.e. the areas without contact dry slower. The image of the glassine paper makes clear that the non-uniform drying (conducted in the same way) results in an uneven shrinkage of the paper. This results in warping: in the areas that dried slowly (within the red circles), the paper lies flatter than in the areas that dried more quickly (experiment con- ducted after Brecht, 1958).

However, all of the existent paper conservation drying methods risk, to some degree that humidity gradients develop within the paper. These risks can nonetheless be reduced, or even eliminated, using some simple measures. In priciple any drying procedure should fulfil the following reqirements:

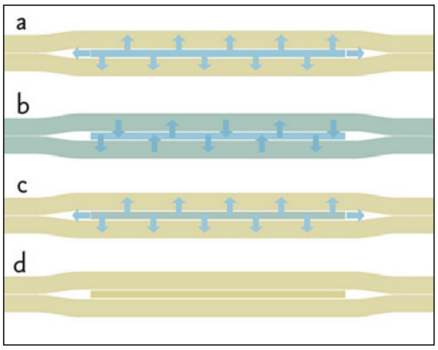
- The paper must be brought into the desired degree of planarity.
- The original surface texture and dimensions of the paper must be optimally restored or preserved.
- All of the qualities of printing and writing media on the paper must be preserved; a special concern is given to textural qualities.
- The method should be as cost-effective as appropriate for the cultural object.

Paper conservators have empirically developed drying techniques that avoid planar distortions caused by a non-uniform water release using, for example, drying under pressure using the so-called contact drying method. Here, the damp paper is placed in a drying stack between hygroscopic materials such as blotters or wool felts, so that water is slowly removed from it, usually under the additional application of light pressure. Water is released into the dry contact materials through capillary action and diffusion. The contact materials, either cellulose-based (blotters) or protein-based (wool felts), pull water from the damp paper which causes an increase in their own water content. The process occurs until equilibrium is reached between the water content of the paper being dried and the contact materials. Then the drying process comes to a standstill. In order for the drying to continue, the established equilibrium must be destabilized and a new concentration gradient created. This is done by exchanging the damp contact materials for dry ones at regular intervals.

This is a discontinuous process that requires time, as a moderate drying speed encourages even drying (Sugarman and Vitale 1992). It is also labour-intensive. Further, the contact materials must be subsequently dried and become distorted. The technical problem of non-uniform drying is therefore transferred from the object itself to the auxiliary materials, and damage to these must be accepted in exchange: (*Fig. 2, on page 4*).

Air-stream drying:

Air-stream drying throughout the process prevents the establishment of an equilibrium between the water content of the material being dried and the contact material. To achieve this, a material that features open air ducts that promote air exchange is integrated into the structure of the drying stack (Futernick 1988, Shure 2000, Minter 2002, Kieffer 2007). The material can be corrugated board or synthetic materials with air channels (Schopfer 2004). Using a forced air dryer, air is continuously moved through the channels, coming in from one end of the stack and moving out the other end.



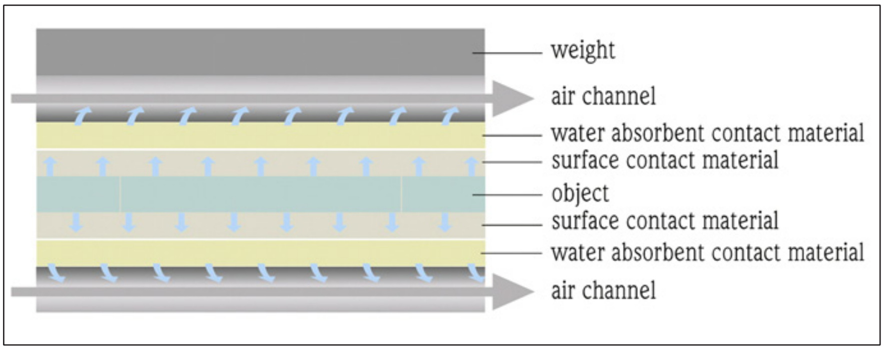


Fig. 2a – d, fig. 3

The water contained in the paper is initially released into the contact material and then moves along the corrugated board in order to establish an equilibrium (*fig. 3*). Since there is a constant gradient in the water vapour's partial pressure between the air and the wall of the air channel, and moreover, since air is continuously moving through the channel, water must also continuously evaporate from the walls and be carried away. The humidity equilibrium between paper and contact materials in the drying stack is therefore permanently destabilized. To re-establish this equilibrium, water must continuously migrate out from inside the stack, i. e. from the paper, to the surface of the air channel, where it then evaporates and is then carried away. This process continues until equilibrium is established between the partial pressure of the water vapour of the moving air and the water in the pore system of the contact materials. At this point, drying is completed. This is an efficient, continuous and uniform drying process that takes effect throughout the paper structure and does not have to be interrupted repeatedly as in traditional contact drying methods that requires the exchange of contact materials. This is labour saving, and the amount of auxiliary materials is thus significantly reduced.

Fig. 2a – d: The principle of contact drying between blotters
The damp object (blue) is placed between dry blotters (yellow). As long as there is a humidity gradient between object and blotters, the water is transferred from the object into the blotters (a). The blotters must be changed several times to disrupt the state of equilibrium over again (b and c) until the drying goal is reached (d). (Banik, Brückle, Paper and water: A guide for conservators, 2011.)

Fig. 3: The principle of air-stream drying
The damp object (blue) is placed between contact materials, i.e. Hollytex (grey), to protect it. It is placed in the drying stack between blotters (yellow) and the material equipped with air channels (grey). As long as there is a humidity gradient between the object and the air passing through the channels, water is released from the object through the blotters into the air stream. (Banik, Brückle, Paper and water: A guide for conservators, 2011.)

Modeling air-stream drying:

To investigate this method, a model drying stack was tested. Here, the air-stream drying apparatus is considered as a thermodynamic system, whose technical parameter of the air-stream and whose material and thermal balance in the course of drying can be calculated. Particular attention is paid here to air turbulence, which is expressed using the Reynolds number (Re). To ensure that the water vapour is transported uniformly along the air-stream channel, thus avoiding humidity gradients inside the system, the air-stream must be as turbulent as possible. The critical Reynolds number for turbulent air streams under normal conditions is 2320.
In general, air streams with a Reynolds number smaller than 0 are laminar. Between 0 and 2320 is considered transitional, during which the laminar flow becomes a turbulent one. In preliminary tests, various drying stacks were connected to enforced air-flow with a flow capacity that could be varied between approximately 135 m^3/h and 270 m^3/h. During the drying procedure, the temperature and the relative humidity of the air was electronically recorded at both the inflow and outlet points of the stack. Two different stack constructions were tested: one stack was constructed primarily of paperboard materials and the other of synthetic ones. (*Table 1*)

Stack construction for paperboard materials	Stack construction for synthetic materials
corrugated board	spacer fabric (polypropylene)
	reinforcing interlayer (polypropylene)
blotter	polypropylene fibre mat
Hollytex™	Hollytex™
object	object
Hollytex™	Hollytex™
blotter	polypropylene fibre mat
	reinforcing interlayer (polypropylene)
corrugated board	spacer fabric (polypropylene)

Table 1: Construction of the test stacks using paperboard materials (left column) and synthetic materials (right column).

To assess the impact of the air-stream's velocity on the outcome of the drying process, a control was established using the traditional contact drying method. Two kinds of paper served as test papers: a historical hand-made paper, and a machine-made paper containing wood and resin-sized. The test papers were pre-treated in an aqueous bath and then shortly placed between polypropylene fibre mats under gentle pressure. The contact drying of the paper in a stack took 4 days. The blotters had to be changed 5 times during the drying period. In this experimental setup, pressure was gauged such that the papers were flattened and the original dimensions and surface structure were preserved as much as possible. For the hand-made paper, the pressure exerted was approximately 0.014 N/cm^2, and for the machine-made ones, it was approximately 0.25 N/cm^2.

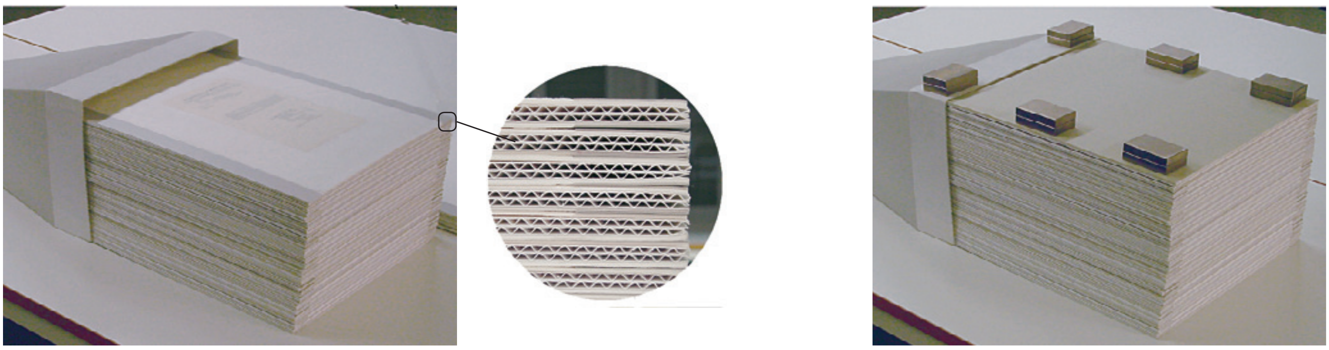


Fig. 4

Using an air-stream drying technique in a corrugated board stack (*Fig. 4*), comparably good drying results could be obtained after only 4 hours, compared to the 4-day drying time in the contact drying method.

It was found that in order to achieve this, the volumetric flow of the air must be under 270 m^3/h (Re approximately 730) at an air temperature of approximately 20 °C and 30 % relative humidity (the prevalent conditions during the experiment). At a higher air stream velocity, humidity gradients as well as tension are produced, causing the paper to warp. In the stack made of synthetic materials, the test papers (under the same conditions) were dry after only 1.5 hours. This is because the non-polar polypropylene fibre material does not realize the sorption forces of hygroscopic materials such as blotters that cause water to be retained.

The release of the water realized in 1.5 hours was too rapid to achieve uniform drying and therefore caused tensions in the paper resulting in waviness. Slowing down the drying time was accomplished by humidifying the inflowing air to a relative humidity of approximately 55 %. The drying time was thereby extended to 4 hours. Nevertheless, the flatness of the paper was not entirely the same as the reference. The experiment could, however, demonstrate that air-stream drying can be controlled and optimized by a targeted conditioning of the inflow of air.

Fig. 4: Air-stream drying technique using corrugated board stacks, system by KLUG-CONSERVATION (Banik, Brückle, Paper and water: A guide for conservators, Fig. 13.26, in print).

Fig. 5a and 5b

Application:

The air-stream drying method was used to restore a children's book from the library holdings of the Kreismuseum Grimma in Saxony, printed around 1850. The book was one of the numerous collection items that were seriously damaged in the floods in the summer of 2002. It was deformed, very soiled, and the body of the book, consisting of 41 pages featuring etchings accompanied by printed text, displayed significant tide lines and foxing (*Fig. 5a*). The pages were surface-cleaned, washed and received a light bleaching treatment to remove soiling, degradation products and improve their visual appearance. Finally, between 13 and 14 pages at a time were dried using air-stream drying in a stack made of cardboard materials at a volumetric flow rate of approximately 135 m^3/h (Re approximately 730) and under a pressure of approximately 0.014 N/cm^2. In order to ensure uniform drying, two layers of blotting paper were inserted as an intermediary layer capable of absorbing water, which extended the drying time to a total of 5 hours. The results of the drying process were good (*Fig. 5b*).

Fig. 5a and 5b: Children's book damaged by flooding (Das Kind, von der Wiege bis zur Schule, by Andreas and Friedrich Perthes, Hamburg and Gotha, c. 1850) from the Kreis-museum Grimma (Saxony), inventory number J 4. 5. Cloth half-binding, with 41 pages measuring 22 x 14.5 cm, body of book of vellum paper with an engraved title page (see image) and 19 engravings by Heinrich Justus Schneider as well as 24 pages of accompanying text by Johann Wilhelm Hey; before treatment (a) and after (b). The pages of the book's body were given a wet treatment to remove the discolourations and dirt deposits, after which they were simultaneously dried and flattened using the air-stream drying technique in a stack made of paperboard materials.

Concluding comment:

In sum, it can be said that to date, air-stream drying is mostly used in cases where large-format single sheets of paper, mostly associated artworks, are to be brought into plane. However, the process is also employed in archives conservation at the Institute for Preservation of Archival and Library Materials (Institute für Erhaltung von Archiv- und Bibliotheksgut, IFE) in Ludwigsburg where it features as the final step in the leaf casting process of documents on a mass scale (Kieffer 2007). Overall, air-stream drying can be considered as a cost-effective method that can be standardize and that can achieve a high-quality drying result. The treatment has potential especially also in situations that require the drying of large numbers of objects, as, for instance, in aqueous paper deacidification, or the recuperation of flood-damaged objects.

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Further information, such as our „Quality Guarantee", certificates of independent testing institutions and information regarding application methods and instructions are stated on our website klug-conservation.com.