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THE DIFFUSION-OPTIMIZED CONVECTION DRYING
TECHNIQUE AND ITS APPLICATION
IN COATING AND PRINTING

by

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The lecture includes:

- Notes on the performance of existing dryers for drying of coated, water-based films.
- Demonstrating the efficiency of diffusion-optimized convection drying for FMP standard dryer and FMP high-performance dryer.
- Explaining the physics of diffusion-optimized convection drying.
- Application of theoretical considerations on the layout of belt, flotation and drum dryers.
- Proposals for the installation of diffusion-optimized convection dryers in practice.
- Conclusions, final remarks and outlook.
OVERVIEW: CONVENTIONAL CONVECTION DRYERS

CONVECTION DRYER with 12 Dryer elements

\[ \dot{m}_T < 1 \frac{g}{m^2 \cdot s} \]

Drying rate

\[ \eta_H < 15\% \]

Energy efficiency

\[ \dot{m}_{Luft} > 10^4 \frac{m^3}{h} \text{ per m}^2 \]

Air requirement

Drying rate by humidity transport:

\[ \dot{m}_T = \frac{m}{L/U_W} \]

Drying rate by energy input:

\[ \dot{m}_P = \frac{\dot{q}}{\Delta h_{LH} - c_p \cdot T_I} \]

Efficiency of energy:

\[ \eta_H = \frac{\dot{m}_T \cdot \Delta h_{LH}}{\dot{q}_{\text{input}}} \]

\[ \Delta h_{LH} = \text{Latent heat} \]

\[ \dot{q} = \text{Required energy per unit area} \]
Similarity requires:
When \( T_g > T_i \), than \( C_g > C_i \), otherwise treatment of heat and mass transfer is not possible.

Theoretical treatment requires
When \( \dot{q}_i > 0 \) and \( \dot{m}_i > 0 \)

Limitations for theoretical treatments of heat and mass transfer hampers the development of advanced methods of drying.

The development of advanced methods to treat heat and mass transfer problems in fluid mechanics is necessary to new and better dryers.

It is essential to extent the theory of drying by generalizing heat and mass transfer treatments without using analogy relationships.
The theoretical treatment of drying is based on the analogy of heat and mass transport:

- Similarity of transport
- Heat transport by conduction and mass transport by convection cannot be treated

Heat transport:

\[ Nu_x = \frac{\alpha \cdot \ell \cdot x}{\lambda} = 0.332 \cdot \sqrt{Re_x} \cdot \frac{Pr}{x} \cdot \left[ 1 - \left( \frac{x_1}{x} \right)^{\frac{3}{4}} \right] \]

Mass transport:

\[ Sh_x = \frac{\beta \cdot x}{D} = 0.332 \cdot \sqrt{\frac{u \cdot x}{v}} \cdot \sqrt{\frac{v}{D}} \cdot \left[ 1 - \left( \frac{x_1}{x} \right)^{\frac{3}{4}} \right] \]
Using similarity of heat and mass transfer allows treatment of simple drying problems.

There is a need for better treatments of drying of fluid films than what is possible today.

Advancements in theory of drying are needed.
QUESTIONS REGARDING TRANSPORT EQUATIONS

Basic equations of fluid mechanics are treated these days in good fluid mechanics books to yield:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_i)}{\partial x_i} = 0
\]

\[
\rho \left[ \frac{\partial U_j}{\partial t} + U_i \frac{\partial U_j}{\partial x_i} \right] = - \frac{\partial P}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_j
\]

\[
\rho \left[ \frac{\partial e}{\partial t} + U_i \frac{\partial e}{\partial x_i} \right] = \frac{\partial q_i}{\partial x_i} - P \frac{\partial U_j}{\partial x_j} - \tau_{ij} \frac{\partial U_j}{\partial x_i}
\]

Basic equations for diffusion transport terms for heat and momentum are derived as follows.

\[
\dot{q}_i = -\lambda \frac{\partial T}{\partial x_i}
\]

\[
\tau_{ij} = -\mu \left[ \frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} \right] + \mu \delta_{ij} \frac{2}{3} \frac{\partial U_k}{\partial x_k}
\]

**Fourier Law**

**Newton’s Law**

Questions come up regarding the general applicability of these equations in fluid flows with temperature and density gradients.
MOLECULAR TRANSPORT TERMS

- Conventional form of diffusion properties:

\[
\begin{align*}
\dot{m}_i &= 0 \\
\dot{q}_i &= -\lambda \frac{\partial T}{\partial x_i} \\
\tau_{ij} &= -\mu \left( \frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} \right) + \frac{2}{3} \mu \delta_{ij} \frac{\partial U_k}{\partial x_k}
\end{align*}
\]

- Extended form of diffusion terms:

\[
\begin{align*}
\dot{m}_i &= -(\rho D) \left[ \frac{1}{\rho} \frac{\partial \rho}{\partial x_i} + \frac{1}{2T} \frac{\partial T}{\partial x_i} \right] = -(\rho D) \left[ \frac{1}{P} \frac{\partial P}{\partial x_i} - \frac{1}{2T} \frac{\partial T}{\partial x_i} \right] \\
\dot{q}_i &= -\lambda \frac{\partial T}{\partial x_i} + \dot{m}_i c_p T \\
\tau_{ij} &= -\mu \left( \frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} \right) + \dot{m}_i U_j + \dot{m}_j U_i + \frac{2}{3} \delta_{ij} \left[ \mu \frac{\partial U_k}{\partial x_k} + m_k U_k \right]
\end{align*}
\]
• Blow-away of the produced vapor results in an acceleration of the evaporation.
• The drying of films is carried out analogously.
• The fluid film is heated and the liquid evaporates; vapor is blown away.
• The partial pressure gradient is generated by blowing.

\[- \frac{\rho D}{P} \frac{1}{x_i} \left( \frac{\partial P}{\partial x_i} \right)\]
If only the partial pressure gradient could be used for drying, the drying of wet streets in winter would not be possible. The street is very cold.

Cold areas can be dried with the transportation term $\rho D \left[ \frac{1}{P} \frac{\partial P}{\partial x_i} - \frac{1}{2T} \frac{\partial T}{\partial x_i} \right]$.

Heat supply results in production of vapor. Heat removal allows further production of vapor.

Vapor removal can be at $\left( \frac{\partial P}{\partial x_i} \right)$ and $\left( \frac{\partial T}{\partial x_i} \right)$. The temperature gradient can be used for the transport of vapor away from the film to be dried.
Considerations for the Gas-Liquid Interface

Heat balance (per unit time per unit area) at the gas-liquid interface:

\[ \dot{q}_{SI} + \dot{q}_{GI} = m \Delta h_{LH} + \dot{q}_L \]

Expressions for \( \dot{q}_{SI} \) and \( \dot{q}_{GI} \):

\[ \dot{q}_{SI} = \frac{(T_H - T_i)}{\left( \frac{H}{\lambda_S} + \frac{h}{\lambda_L} \right)} \]
\[ \dot{q}_{GI} = \lambda_G \frac{dT}{dy} \]

The balanced equation:

\[ \left(1 - f\right) \frac{(T_H - T_i)}{\left( \frac{H}{\lambda_S} + \frac{h}{\lambda_L} \right)} + \lambda_G \left[ \frac{dT}{dy} \right]_{I/G} = \frac{\mu_G \Delta h_{LH}}{2T_i} \left[ \frac{dT}{dy} \right]_{I/G} \]

The temperature gradient at the gas-liquid interface:

\[ \left[ \frac{dT}{dy} \right]_{I/G} = \frac{\left(1 - f\right) \frac{(T_H - T_i)}{\left( \frac{H}{\lambda_S} + \frac{h}{\lambda_L} \right)} + \lambda_G \left[ \frac{dT}{dy} \right]_{I/G}}{\left( \frac{\mu_G \Delta h_{LH}}{2T_i} \right) \left( \frac{H}{\lambda_S} + \frac{h}{\lambda_L} \right)} \]

\[ f = \text{Loss factor} \]
Expressions for gas-liquid interface temperature, mass diffusion rate and drying time

**Gas-Liquid Interface Temperature:**

\[
T_I = T_G - \frac{(1 - f) \cdot (T_H - T_I) \cdot \exp \left( \frac{m \cdot C_P}{\lambda_G} \cdot \delta_G \right) - 1}{m \cdot C_P \cdot \left( \frac{\mu_G \cdot \Delta h_{LH}}{2 \cdot \lambda_G \cdot T_I} - 1 \right) \cdot \left( \frac{H}{\lambda_S} + \frac{h}{\lambda_L} \right)}
\]

**Mass diffusion rate (per unit area):**

\[
m = \frac{(1 - f) \cdot \mu_G \cdot (T_H - T_I)}{\left( \mu_G \cdot \Delta h_{LH} - 2 \cdot \lambda_G \cdot T_I \right) \cdot \left( \frac{H}{\lambda_S} + \frac{h}{\lambda_L} \right)}
\]

**Drying time:**

\[
t_d = \frac{M \cdot \rho_L \cdot h \cdot \left( \frac{\mu_G \cdot \Delta h_{LH} - 2 \cdot \lambda_G \cdot T_I}{\lambda_S} + \frac{h}{\lambda_L} \right)}{(1 - f) \cdot \mu_G \cdot (T_H - T_I)}
\]
Case I: Variation of $T_I$ with $T_G$

$\delta_G = 300 \mu m$
$H = 100 \mu m$
$h = 10 \mu m$

$T_H = 295K$

Case II: Variation of $T_I$ with $T_H$

$T_G = 350K$
Case I: Variation of $m$ and $t_d$ with $T_G$  

\[ T_H = 295K \]

\[ T_H = 295K \]

Case II: Variation of $m$ and $t_d$ with $T_H$

\[ T_G = 350K \]

\[ T_G = 350K \]
DATA FOR HIGH-PERFORMANCE DRYER

For the blown air flow $\dot{V}_{\text{Air}}$ applies: $\dot{V}_{\text{Air}} = A_{\text{Air}} \cdot U_{\text{Air}}$

$A_{\text{Air}} = \text{provided blowing area}$

$U_{\text{Air}} = \text{velocity of blown air}$

$m_T \sim A_{\text{Air}}, \sqrt{U_{\text{Air}}}, \sqrt{1/d}, \Delta T$

Outlet

Fluid layer

Inlet

Outlet

Temperature

Density

Temperature (K)

Density (kg/m³)
The calculations show:
- High drying rates in the range of blowing.
- Low drying rates in the field of suction.

- The standard dryer has an inblow area of $54 \cdot 10^{-3}$ in flow direction with 1m width.
- The high-performance dryer has an inblow area of $90 \cdot 10^{-3}$ in flow direction with 1m width.

$$\dot{m} = 13.37 \frac{g}{m^2 \cdot s}$$

$$\dot{m} = \text{mass transfer of air and moisture}$$

$$(\dot{m}^T) = 1.67 \cdot (\dot{m}^T)^{ST} \approx 11 g/m^2 s$$
Volume flow of supply air: 

\[ \dot{V} = U_{Air} \cdot A_{Air} \]

- \( U_{Air} \): Blow-out velocity out of the nozzles for the supply air
- \( A_{Air} \): Opening Area of the blow-out nozzles

With respect to the optimization of the drying rate is the question arises, which of the above-given nozzle layouts brings benefits.

\[ \dot{m} \sim A_{Air}, \sqrt{U_{Air}} \sim \]

It follows \( A_{Air} \) large, \( U_{Air} \) small
DRYER MODULE, DRYER UNIT AND DRYER ELEMENT

Drying Efficiency
less energy consumption. increased drying rate

- 750 mm dryer element
- 500 mm dryer element
- 250 mm dryer element
COATING WITH A SLOT NOZZLE
The drying rate to be determined can be calculated using the following formula from the test results:

\[ \dot{m}_T = \left( \frac{m}{L} \right) U_W \]

In the test rig the drying length is fixed. So the determination of \( \dot{m}_T \) takes place by the adjustment of the coating velocity, so that the layer after the dryer is measured as dried.

Measured drying rates can be extrapolated on plants in practice.

The installed dryer length is one meter and hence the coating velocity needs to be adjusted to the measured drying rate.
Drying Rate of FMP Dryer (3)

- Aims of further development, $U_{\text{air}} = 4.8 \, \text{m/s}$
- Aims of further development, $U_{\text{air}} = 1.6 \, \text{m/s}$
- Ventilator with full power, $U_{\text{air}} = 0.8 \, \text{m/s}$
- Ventilator with half power, $U_{\text{air}} = 0.4 \, \text{m/s}$
- Ventilator with full power, tests for customer 1
- Ventilator with half power, tests for customer 2

Drying rate [kg/m².s]

Region of drying rates of existing dryers

Top Temperature [°C]
TWO DIFFUSION-OPTIMIZED CONVECTION DRYERS

Installation situation of the 2 x 1 m long FMP-dryer
Installation situation of the FMP dryer modules
Subsequently introduced roller packs for stabilizing the paper web. (The picture shows the paper web from below.)
EXPERIMENTAL RESULTS IN LABORATORY MACHINE OF THE PAPER INDUSTRY

Experimental parameters:

- Fluid: Coating color with TG 33%
- Web velocity: 50 – 80 m/min
- Dryer length: 2 m
- Drying width: 520 mm
- Coating width: 500 mm
- Drying temperature: appr. 180°C
- Blowoff: 1.5 – 2 m/s

<table>
<thead>
<tr>
<th>Grammage [g/m²]</th>
<th>Web velocity [m/min]</th>
<th>Drying rate [g/m²s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>50</td>
<td>4.19</td>
</tr>
<tr>
<td>15</td>
<td>75</td>
<td>6.28</td>
</tr>
<tr>
<td>15</td>
<td>80</td>
<td>6.7</td>
</tr>
</tbody>
</table>

- There is no increase in the drying rate due to the web velocity.
The FMP dryer doesn’t overheat the substrate. At the end of the dryer only the temperature is controlled. The control of the drying is only done by layout and temperature measurements at the end of the dryer.

FMP is developing a high-performance dryer based on the diffusion-optimized convection drying technique. Its drying rate is:

\[ \dot{m}_T = 11 \frac{g}{m^2 \cdot s} , \]

1.67 times higher than that of the FMP standard dryer.
TRANSFER OF TEST RESULTS

Air supply pipe
Air exhaust pipe
FMP-Dryer

Result of pilot plant
Result of the FMP plant

Graph showing:
- Aims of further development $U_{air}=4.8 \, \text{m/s}$
- Aims of further development $U_{air}=1.6 \, \text{m/s}$
- Ventilator with full power ($U_{air}=0.8 \, \text{m/s}$)
- Ventilator with half power ($U_{air}=0.4 \, \text{m/s}$)
- Ventilator with full power, tests for customer 1
- Ventilator with half power, tests for customer 2

Drying rate $[\text{kg/m}^2\cdot\text{s}]$

Region of drying rates of existing dryers

Top Temperature $[\text{°C}]$

Values:
- 6.7
- 180
Belt dryer for tin sheet to dry a water-based layer of 2 µm in thickness, resulting in drying rates of:

$$m_T = 11 \, g/m^2s$$

(extrapolation from measurements for $m_T^{ST}$). The distance to the belt was 8mm on both sides.

The dryer also turned out to be an aerodynamic sheet guide, i.e. belt fluctuations were suppressed by the airflow. The belt ran without any notable lateral motion.
PHOTOGRAPHY OF THE INSTALLED BAND DRYER
RESULTS WITH THE BAND DRYER

Preliminary tests have been run on a test facility of the company August Koehler SE, which showed that the standard dryers of FMP TECHNOLOGY GMBH can reach a drying performance of:

\[ \dot{m}_T = 6.7 \text{ g/m}^2\text{s} \]

The high-performance version of the FMP-dryer, which was applied in the present project, provides a performance increase factor of 1.67, so that for the expected performance of the dryer the following value could be specified:

\[ \dot{m}_T = 11 \text{ g/m}^2\text{s} \]

Further drying performance improvements are possible, which are best reached via the distance to the layer to be dried. This performance increase is energy neutral.

The dryer has different parameters that allow the drying rate to be controlled. For “thermal papers” \( T_i \), not \( \Delta T \), needs to be low.
PRODUCTION AND TRANSPORTED MASS FLOW RATE

\[ d=4\text{mm, } u=1\text{m/s and } \Delta T = (T_g-T_i)=200 \]

![Graph showing drying rates and mass flow rates with labels for mass production, mass transport, drying rates of conventional dryers, and mass flow.]
NEW TESTRIG: DRUM OR BELT DRYER

Coating plant with drying

1 m FMP dryer
2 m FMP dryer
Circulating carrier tape

Slot nozzle coating
Coating station
Unwinding
Winding
Calculation of drum diameter: \[ D \approx \frac{1}{\pi} \frac{m}{m^T} \cdot U_W \]

- With \( U_W = 6 \text{ m/s} \), \( m = 10 \frac{g}{m^2} \) and \( m^T = 35 \frac{g}{m^2 \text{s}} \), it follows: \( D \approx 0.6 \text{ m} \).

- The time of using long dryers is over. Plants with “compact dryers” are possible.

- Systems with UV dryers can be built similarly short with thermal dryers.
APPLICATION POSSIBILITIES

Needed dryer length \( L = \frac{m}{m_t} \cdot U_W \)

With newly installed dryers it is possible to manage the process with 1/5 to 1/10 of the dryer length.
The presentation:

- goes into the convection drying technique used nowadays in paper finishing.
- underlines the long convection dryer resulting with this drying method.
- shows that diffusion-optimized dryers are possible. The theory for this is available.
- Own verification experiments and results from experiments in the paper industry as well as in the common coating industry were shown.
- For FMP dryers, the following drying rates could be reached:
  \[(m^T)^{ST} = 6,7 \, \frac{g}{m^2 s}, \quad (m^T)^{HT} = 11 \, \frac{g}{m^2 s}\]. These values are improvable by a factor of \(\approx 3.3\).
- Short convection dryers are easily possible. Savings in dryer length by a factor of 1/5 to 1/10 with respect to existing convection dryers are foreseeable.
- Booster dryers for existing plants were presented and also drum dryers for new installations.