Designing a sensor for local heat transfer in impingement driers

L. Wengeler, M. Schmitt, P. Cavadini, P. Scharfer, W. Schabel,

Institute of Thermal Process Engineering, Thin Film Technology
Karlsruhe Institute of Technology (KIT), D-76131 Karlsruhe, Germany

Presented at the 15th International Coating Science and Technology Symposium,
September 13-15, 2010, St. Paul, MN[1]

Introduction

In technical dryers, foils, films and coatings are conventionally dried by impingement of conditioned gas. The drying process can be described by taking into account the diffusion within the film, the phase equilibrium at the film surface and the convective mass transport in the gas phase [1]. Phase equilibrium and diffusion within the film relate on material properties that can be measured in laboratory experiments. The heat and mass transfer in the gas phase can be described by transfer coefficients. These coefficients are described by empirical correlations as a function of standard geometries and gas flow rate and related to each other through the Lewis correlation [2]. However, technical driers often vary from these standard geometries making a precise dimensioning or scale-up impossible. Especially for drying sensitive films for organic photovoltaic [3] or light emitting diodes (OLEDs) [4] it is important to achieve a homogeneous drying in cross web direction, requiring knowledge of the local values of the transfer coefficients. Two approaches to access this quantity are simulation and measurement. Simulations are difficult because geometries have to be adjusted to every new drier. As well the boundary conditions are not always well defined. Most measurements technique measure either mass or heat loss of a certain area and are difficult if not impossible to perform within a technical environment. The goal of this paper is to detail the construction and application of a simple sensor for on site point measurements of the local heat transfer coefficient.

Sensor Design

The major challenges for the design are:

- user friendliness,
- small device thickness without edges to minimize the alteration of the normal flow pattern within the drier,
- compensation for heat transport to both sides, as most driers heat the substrate from both sides,
- and small measurement area to allow for local measurement.

In principle it is possible to measure either mass or heat transfer coefficients and calculate the value of the other through the Lewis correlation (WA, 2009). However mass transfer based measurements are often quite messy and thus not very user friendly. For heat transfer measurements one can either measure the heat uptake or the heat loss. Keeping in mind the constrain of small device thickness the heat loss measurement is favorable as it is easier to introduce energy into a small volume than to extract or store it. Thus the sensor is heated and the heat loss to the cold drying air is recorded. The heat is introduced through a heating foil (40X60 Heizfolie, Conrad Electronic) which is isolated to both sides with 5 mm polystyrene sheets. The sheete are glued together using conventional spray-on-glue (Sprühkleber, Conrad Electronic) Temperature is measured using thin wire thermocouples (SA1-T1-3M, Type K, Omega) at the heating foil, at the surface of the isolating sheets and in the cold drying air T_U . The temperature gradient through the polystyrene will be linear in stationary operation and allows the calculation of the heat flux on both sides and the application of thin wire thermocouples realize small measurement areas of only a few mm. To minimize air distortion at the edges at both sides, a PET foil is applied that can be taped into the substrate.

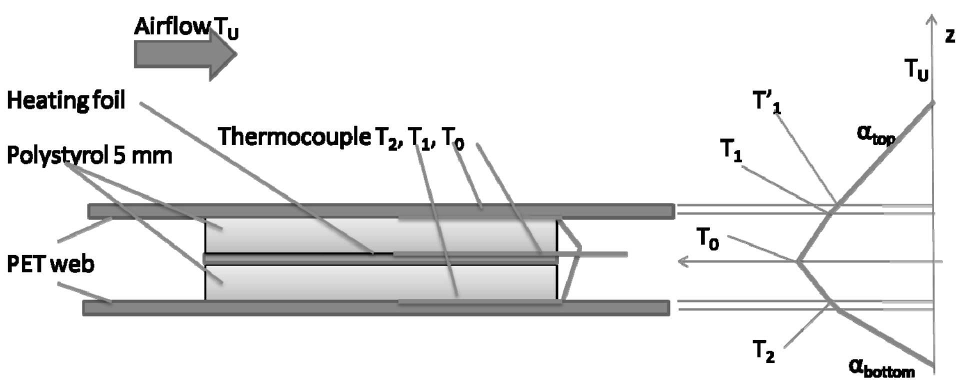


Figure 1: Shematic sketch of the sensor (left) and qualitative representation of the temperature within the cross section (right).

For a given heat flux, the temperature at the surface T'_1 can be calculated for a known heat conductivity and thickness of the PET foil. Subsequently the heat transfer coefficient can be computed from surface temperature and bulk air temperature:

$$\frac{\dot{Q}}{A} = (T_0 - T_1)\frac{\lambda_{PS}}{\delta_{PS}} = (T_1 - T_1^{'})\frac{\lambda_{PET}}{\delta_{PET}} = (T_1^{'} - T_U)\alpha_{Top} \quad (1)$$

The accuracy of the temperature measurement and the thickness of the isolating sheet determine the achievable measurement accuracy.

Experimental

To calibrate the sensor a temperature gradient is applied using temperature controlled plates at both sides without connecting the heating foil. Now the temperature at the top, center and bottom is recorded. The heat flux of both isolating sheets as well as the overall heat flux has to be equivalent. This measurement can be repeated for several temperature gradients, giving an effective factor that correlates heat flux to temperature difference.

The sensor is now introduced into the drier and the heating foil is powered with 12 VDC. The thermocouples are continuously recorded (USB-TC, Plugin) and displayed. Depending on the drier setting, it takes several minutes to reach a stationary point. Now the temperatures are logged for one minute providing the data for this position. Subsequently the sensor is positioned at the next measurement point and the procedure is repeated. Positioning was done manually by measuring the distance from the center and from the next nozzle with a metering stick. To ensure that the flow pattern does not change due to the introduction of the sensor, the ratio of sensor thickness to distance between nozzle (=0.07 in the presented setup) and the ratio of typical web speed to air velocity (=0.005 in the presented setup) has to be small.

The average relative deviation of the measured value due to positioning errors was determined in a laboratory scale experiment by repeated measurements at the same point after manual positioning to be 7.6 %.

Results and Discussion

The sensor was employed to measure a grid of four by four points within on section of technical drier. Figure 2 shows a linear interpolation of the measurement data. A hot spot with almost twice the heat transfer coefficient compared to the lowest part can be seen at lower right corner.

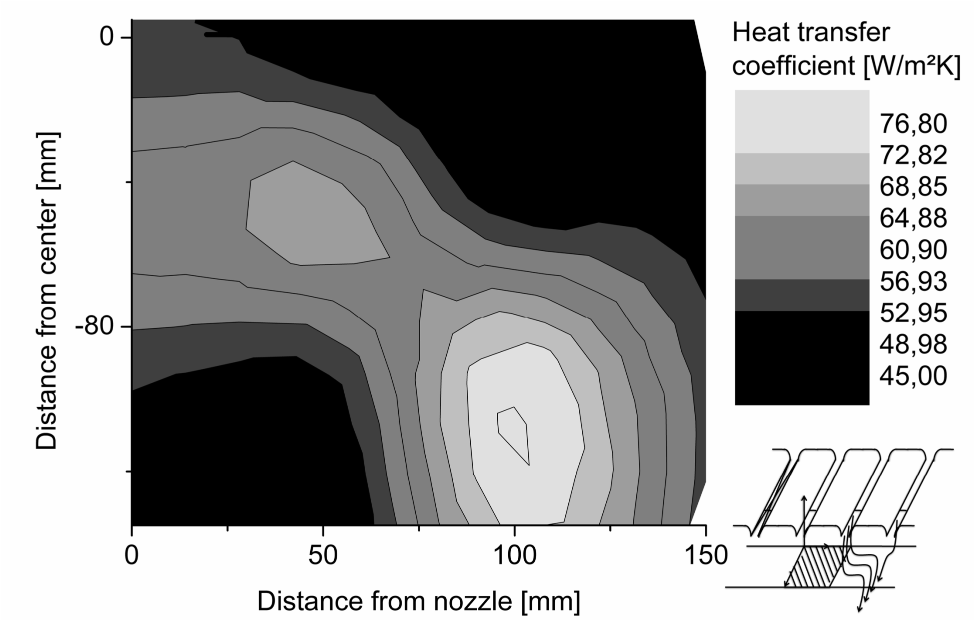


Figure 2: Interpolation of 4 by 4 measuring points in one section of a technical drier (left). Shematic sketch of the drier. The shaded rectangle indicates the measurement area.

The hot spot is caused by the effluent air which is accelerated to the side in direction of the air exit. The large local variation of the heat transfer coefficient shows the potential for this measuring technique.

Most important for drying is the integral heat transfer coefficient in web direction as a function of the cross web distance. These results are shown in figure 3 where the bars indicate the variation in web direction at the given cross web position. For this drier even though the local values vary quite strongly the integral values are much more homogeneous with only a slightly lower value at the center of the drier.

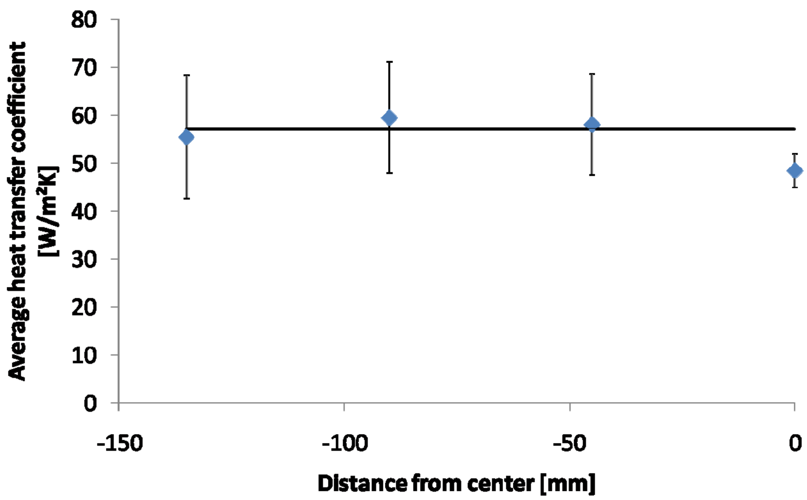
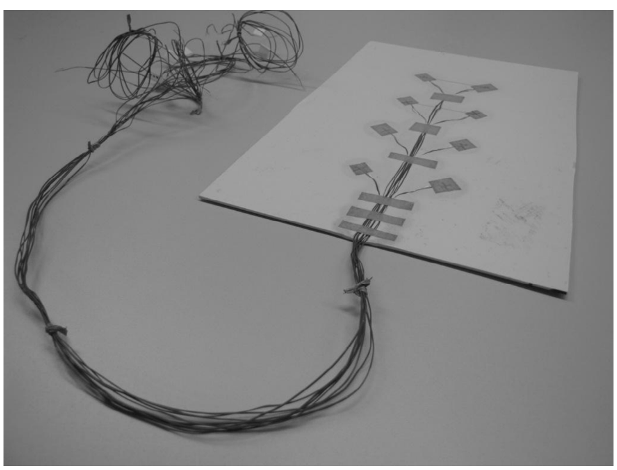


Figure 3: Local heat transfer coefficient, averaged in web direction as a function of the cross web distance.

The straight line indicates the value calculated for this drier using the correlation by Martin and Schabel [2] thus measured values are in good agreement with literature.

Outlook: Employing a sensor array

The biggest experimental error is the manual positioning of the sensor. We are currently investigating a new design with a multiple sensor array that will eliminate this weakness as well as speed up the measurement (Figure 4, left).



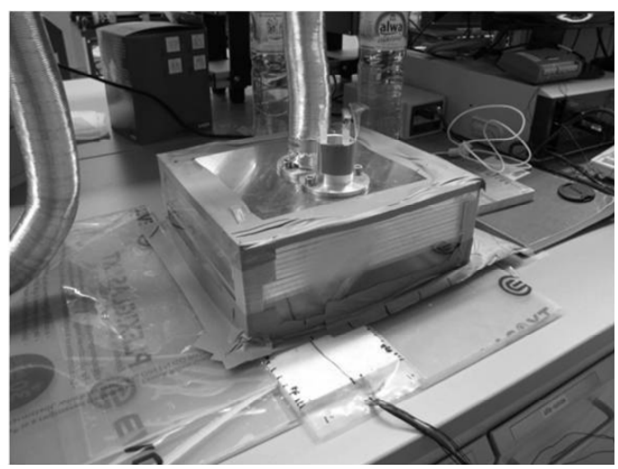


Figure 4: Photo of the new multi point local heat transfer sensor (left). Setup for the optimization of impinging jet driers for homogeneous drying (right).

A comparison to fluid dynamic simulation is currently in progress. First results support the measurement of strongly inhomogene transfer coefficients in impinging jet driers. For the optimization of impinging jet driers with respect to drying homogeneity a setup is currently under construction applying liquid thermo crystals for heat transfer measurements Figure 4, right.

References

[1] **Schabel, Wilhelm und Martin, Holger. 2006.** G10 Impinging jet flow heat transfer. [Buchverf.] VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen. *VDI-Wärmeatlas*: Springer, 2006.

[2] **Martin, Holger. 1973.** *Stoffübergangsversuche und strömungstechnische Berechnungen zur Ermittelung einer optimalen Schlitzdüsenanordnung für Prallstrahltrockner.* Karlsruhe: 1973.

[3] **Schmidt-Hansberg, Benjamin, et al. 2009**. Drying of thin film polymer solar cells. *European Physical Journal Special Topics*. 2009, 166, 49-53.

[4] **Holst Centre. 2009**. Lichtgevend behangpapier stap dichter. Eindhoven : Press Release, 26. May 2009.