THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE GAS PHASE MASS TRANSPORT ON FLAT PLATES IN LAMINAR FLOW

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Introduction

Local measurements of the solvent content during drying [1,2] have shown varying local mass transfer coefficients along the coated surface in flow direction and a moving drying front due to a laterally inhomogeneous gas phase resistance. For an accurate interpretation of the measurement data the local mass transfer coefficient has to be known. The characterization of the gas phase conditions can be done in additional experiments or theoretically [3, 4].

A common geometry for drying experiments is the flat plate, which is arranged parallel within a forced flow in a drying channel. For this geometry the boundary layer theory is an often used approach to calculate the gas side mass transfer coefficient. Correlations for the integral and local mass transfer coefficient exist. For comparison with the numerical and experimental results a prevalent correlation after Brauer [5] is used in this work.

$$Sh_x = 0.332\, Sc^{1/3} {Re_x}^{1/2} \cdot \left[1 - \left(\frac{x_0}{x}\right)^{3/4}\right]^{-1/3} \qquad (1)$$

This analytically derived correlation considers a shift x_0 of the mass transfer region against the beginning of the semi-infinite plate by means of an additional term. In a real experimental setup of a flow channel including a substrate plate, the resulting boundary conditions for the fluid dynamics can be slightly different.

Experimental setup

To monitor the drying kinetics in situ, laser light (635 nm) was reflected at 5 distinct positions as shown in Fig. 1 under an incident angle in the range of 25-35° (depending on the setup) and detected by a Si photodiode during coating and the following drying period. Hence the film thickness is monitored instantly after film casting at 5 distinct positions simultaneously. More information about this technique is available in reference [2,6].

a) b)

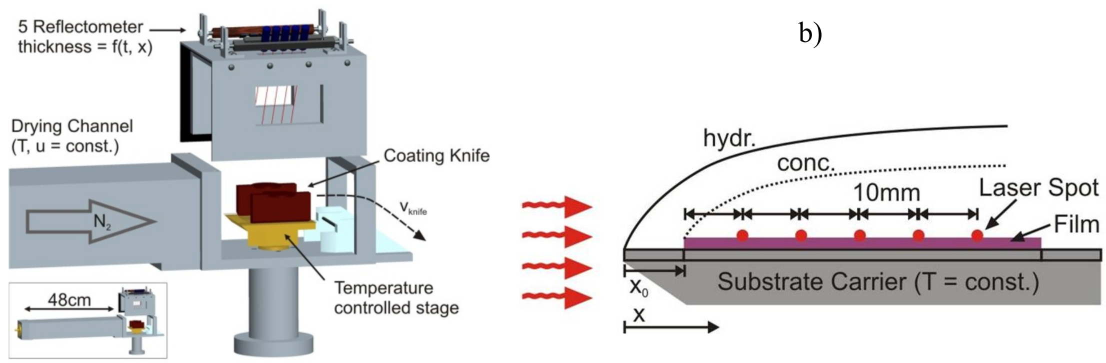

Fig. 1: a) Schematic drawing of the drying channel with integrated knife coater and linear array of five monochromatic reflectometers. The inset shows the 40 cm long channel for airflow distribution in front of the coating stage. b) illustrates the position of the film at the stage and the laser spots for thickness measurement.

Based on the time resolved thickness measurements the local mass transfer coefficient can be determined as described in reference [2,6] with the film shrinkage averaged over 10 data points at the beginning of the drying at each position. The mass transfer coefficient was then derived from a linear mass transfer kinetic and a mass balance for the drying film.

Numerical simulation and evaluation

For the numerical simulation [7] of the continuity and momentum equations an element-based finite-volume computer code, which is mostly second order accurate, has been used. The geometry has been split into the inlet zone and the part of the channel with the plate, including the upstream region influenced by pressure gradients. To simulate the thin film drying on top of the substrate plate, an evaporation area was implemented on the surface of the substrate plate. On the evaporation area a constant partial pressure was set as boundary condition. This corresponds to a constant rate drying behavior of a coated solution. The local mass transfer coefficient can be ascertained from the simulation results taking the concentration gradient in the gas phase on top of the evaporation area. More information can be found in the reference [7].

Results and Discussion

In the experimental and numerical investigation the range of gas velocity was varied between $u_0 = 0.15 - 0.5\,\frac{m}{s}$ with a constant shift $x_0 = 10\ mm$ of the mass transfer region against the beginning of the substrate plate.

To compare the analytically derived Sherwood correlation after Brauer [5] with experimental and calculated data, the local mass transfer coefficients are written as local Sherwood numbers $\left(Sh_x = \frac{\beta_{i,x}\cdot x}{\delta_i}\right)$. In addition, the correlation after Brauer was fitted against the experimental data with two parameters.

$$Sh_x^{fit} = 0.07919\, Sc^{1/3} {Re_x}^{0.7234} \cdot \left[1 - \left(\frac{x_0}{x}\right)^{3/4}\right]^{-1/3} \tag{2}$$

Vortices and boundary separation cannot be predicted by the analytically derived correlation [6] based on the boundary layer equation, therefore the comparison shown in Fig. 2 differs for increasing gas velocity.

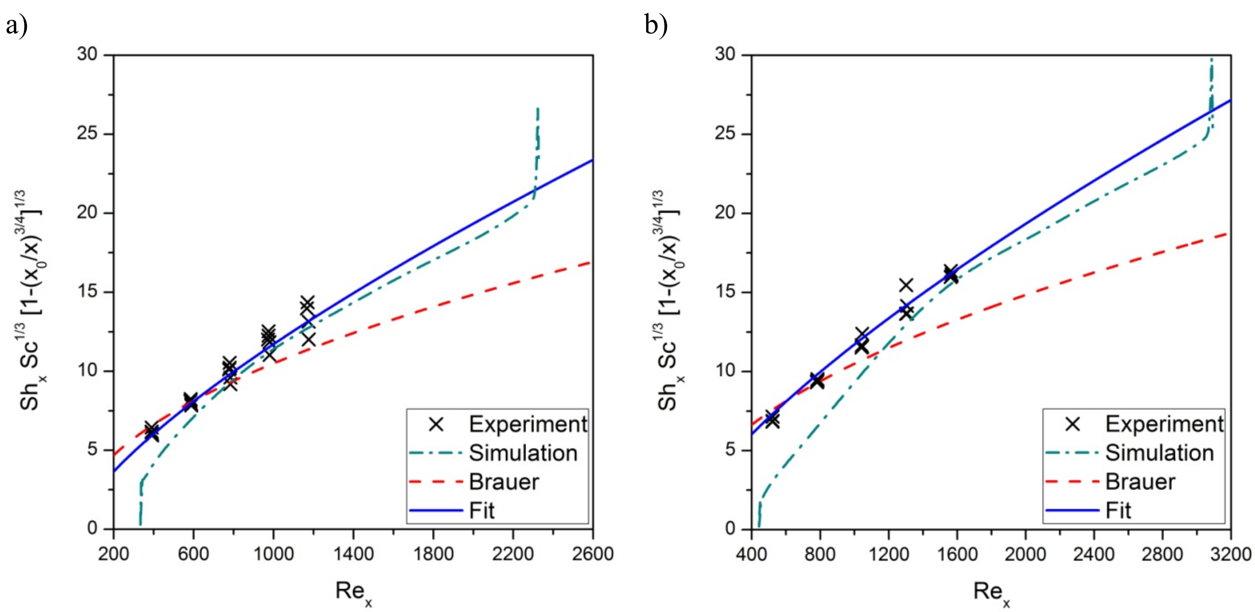

Fig. 2: Comparison of the numerical and experimental Sherwood numbers with the analytically derived correlation [5] and the adapted correlation [2] at different mean velocities a) $u_0 = 0{,}3\ m/s$ and b) $u_0 = 0{,}4\ m/s$.

For the non-ideal geometry of the investigated setup a vortex at the anterior top of the plate occurs. This vortex is predicted by the numerical investigation, but the influence on mass transfer is exaggerated for higher gas velocities. The occurrence of turbulences in the front vortex will lead to a higher mass transfer and thus to better correspondence to the experimental results. Up to now, no turbulence model has been proofed.

Based on these findings [2,7] the geometries of future setups for the investigation of drying processes can be optimized to match the simplifications for a description by analytically derived correlations. This is an important step for a valid interpretation of drying experiments.

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