

Laser-induced Luminescence Technique for the Measurement of Local Temperature Distributions in Thin Wavy Liquid Films

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Abstract Heat transfer in falling liquid film systems is enhanced by waviness. Comprehension of the underlying kinetic phenomena requires experimental data of the temperature field with high spatiotemporal resolution. Therefore a non-invasive measuring method based on luminescence indicators is developed. It is used to determine the temperature distribution and the local film thickness simultaneously. First results are presented for the temperature distribution measurement in a laminar-wavy water film with a liquid side Reynolds number of 126 flowing down a heated plane with an inclination angle of 2°. The measured temperature distributions are used to calculate the local heat transfer coefficient from the wall to the liquid for different points in the development of a solitary wave.

1. Introduction

The liquid phase in applications of chemical and life science industry, like film evaporators, absorption heat pumps and falling film reactors, often occurs as gravity driven flow in form of thin liquid films. It is observed that heat and mass transfer in wavy film flow is significantly higher than in a smooth film. A variety of investigations have been performed to analyze heat and mass transfer resulting in semi-empirical correlations to describe transfer enhancement in such film systems, see Brauner and Maron (1982), Wasden and Dukler (1990), Conslisk (1995), Alekseenko et al. (1996), Alhousseini et al. (1998), Roberts and Chang (2000) and Miladinova et al. (2002). For a critical review of models of coupled heat and mass transfer in falling film absorption see Killion and Garimella (2001). The mechanisms of transport processes leading to the enhancement of heat transfer in such systems are not clarified in detail. Because of the complexity of the system it is not possible to identify the responsible transport mechanism from integral measurements of heat transport.

To analyze these phenomena in detail, heat transfer in falling liquid films is investigated in the Collaborative Research Center (SFB) 540 "Model-based Experimental Analysis of Kinetic Phenomena in Multi-phase Fluid Reactive Systems". To gain deeper insight two essential objectives were pursued: to identify the precise hydrodynamic regime in falling liquid films and to obtain highly resolved experimental data on the temperature distribution in a heated film.

The small film thickness requires a non invasive measuring method to avoid disturbance of the film. There exist some well developed non-invasive optical measurement techniques e.g. laser doppler anemometry (LDA) and particle image velocimetry (PIV) for velocity field measurement. Measurements of the velocity field in wavy film flow were performed by Al-Sibai et al. (2002). For information about local film thickness a chromatic confocal imaging method can be used, see Lel et al. (2004). For temperature field measurements thermo-chromic liquid crystals (TLC) were used. For example, Günther and Rudolf von Rohr (2000, 2002) measured temperature and velocity fields in turbulent natural convection by combining PIV and liquid crystal thermography (LCT). Temperature field measurements of thermal convection from a heated horizontal surface applying two-color laser induced fluorescence (LIF) were performed by Sakakibara and Adrian (1999). In order to get field information about velocity and temperature simultaneously a combination of PIV and planar laser induced fluorescence (PLIF) is used. Hishida and Sakakibara (2000) used this method to investigate impinging jets. In the cases where PLIF is used to get information about the

temperature distribution, the region of interest has to be optically accessible in two perpendicular planes to realize the planar laser sheet and to measure the emission of the excited indicator. This results in certain geometrical restrictions for the systems to be investigated.

The proposed optical method presented in this paper makes use of optical probes which allow to provide the temperature distribution in a film flowing down a heated plane and the local film thickness simultaneously in both high spatial and high temporal resolution. The measurements are possible at several user-defined points of interest at the same time. The data obtained from the presented measurements is used to determine the local heat transfer coefficients in a single wave.

2. Physical Basics

For the investigation of the heat transport in a laminar wavy liquid film of water the optical indicator biacetyl (2,3-butanedione) is used. It emits phosphorescence as well as fluorescence when illuminated with UV-light. In an aqueous solution the phosphorescence and fluorescence intensity depend on temperature and indicator concentration. Furthermore the phosphorescence is quenched by dissolved oxygen in the water whereas the intensity of fluorescence is independent of oxygen. The latter interrelationship was used to measure concentration distributions C of absorbed oxygen in laminar wavy liquid films, see Schagen and Modigell (2005).

After a pulsed excitation with UV-light the phosphorescence emission I decreases with time according to

$$I(C, \vartheta) = I_0(C, \vartheta) \exp(-t / \tau(C, \vartheta)) \quad (1)$$

In this equation I_0 is the initial emission intensity after turning off the excitation and τ is the decay constant of the phosphorescence emission.

In this work only oxygen free aqueous solution $C = 0$ is used and so the phosphorescence emission depends only on temperature. Measurements have been performed to analyze the correlation between the temperature and the decay constant of the phosphorescence emission using the optical device described in the following section. The temperature dependency of the phosphorescence decay constant was measured in the range from 10 to 30 °C and the experimental data can be approximated with the linear equation

$$\tau(\vartheta) = -3.4 \cdot 10^{-6} \text{ s}/^\circ\text{C} \cdot \vartheta + 2.99 \cdot 10^{-4} \text{ s} \quad (2)$$

with a residual norm of $2.94 \cdot 10^{-6}$ and a mean standard deviation of $2.3 \cdot 10^{-5}$ s. The measurement at $\vartheta = 20$ °C is in good agreement with the value of Bäckström and Sandros (1958) who reported a value of $\tau = 229$ μs. The measurement of Almgren (1967) of 201 μs at 25 °C was obtained with a higher concentration of biacetyl in aqueous solution which possibly caused higher self quenching rate of the phosphorescence emission.

By measuring the decay of the phosphorescence in an isothermal system of aqueous biacetyl solution the temperature can be simply determined. Describing the measured data by applying Eq. (1) the decay constant τ is obtained. Finally, making use of Eq. (2), the temperature can be calculated.

In case of a non-uniform temperature distribution in a stagnant liquid film every volume element emits a specific phosphorescence after excitation, depending on the local temperature, as sketched in Fig. 1.

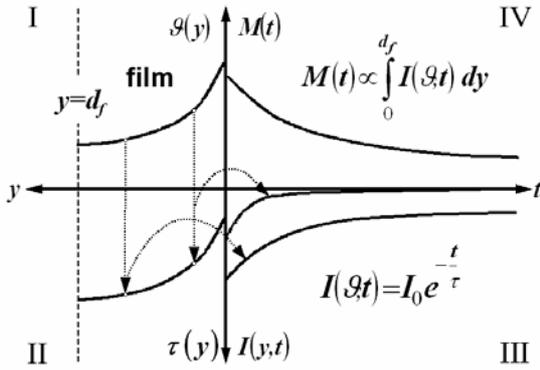


Fig. 1. Dependence of measured signal $M(t)$ on temperature profile $\vartheta(y)$ in a stagnant liquid film.

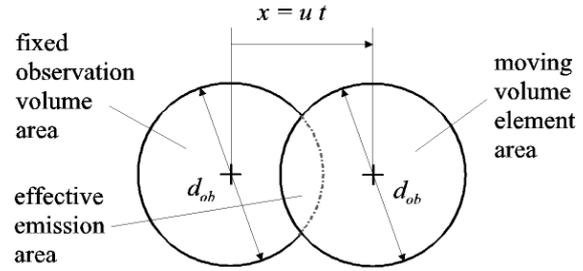


Fig. 2. Effective emission area of a volume element within the moving liquid film.

In quadrant I a temperature profile in a liquid film is qualitatively shown as a function of the coordinate y , which is oriented perpendicular to the surface of the film. The surface of the film is indicated by d_f . Quadrant II shows the corresponding course of the local decay constant also as a function of y . The local initial intensity and the respective time dependent specific phosphorescence intensity emitted from two locations in the film, indicated with the arrows, are drawn in quadrant III. The phosphorescence totally emitted by all volume elements along the coordinate y is given by the integral equation as indicated in quadrant IV in Fig. 1.

Finally, the total intensity $M(t)$ emitted by the observation volume in a flowing liquid film is influenced by the velocity distribution $u(y)$. During the measurement volume elements containing excited biacetyl molecules move out of the fixed observation volume due to their local velocities. The resulting superposed decrease of the measured signal can be modeled based on the residence time of excited biacetyl molecules within the observation volume. This leads to

$$M(t) = K \cdot \int_0^{d_f} n_1(y, t) I(\vartheta, t) dy \quad (3)$$

The factor K contains apparatus and device specific contributions to the optical signal which can be assumed to be constant. The function n_1 is the distribution of the luminescent area within the cross section of the measurement volume, see Fig. 2, and can be modeled as

$$n_1(y, t) = \frac{2}{\pi} \left[\arccos\left(\frac{u(y)t}{d_{ob}}\right) - \frac{u(y)t}{d_{ob}^2} (d_{ob}^2 - (u(y)t)^2)^{1/2} \right] \quad (4)$$

using basic geometrical relations.

The exact velocity field in our experiment is unknown. Yet the velocity distribution in flow direction $u(y)$ in wavy films can be approximated by a parabolic profile

$$u(y) = u_{\max} \left[2 \frac{y}{d_f} - \left(\frac{y}{d_f} \right)^2 \right] \quad (5)$$

comparable to the analytical solution of Nusselt (1916). Here the parameter u_{\max} is the longitudinal component of the local surface velocity, see e.g. Alekseenko et al. (1994) and Al-Sibai et al. (2002). Based on experimental investigations on film flow of Adomeit et al. (2000) and Al-Sibai et al. (2002) we propose a linear interpolation of the surface velocity within the film thickness region $d_{f,m}$

$d_f < d_{f,max}$. Thus the longitudinal surface velocity component can be calculated:

$$u_{max} = \begin{cases} u_{max,Nu} = \frac{g \sin \phi}{\nu} d_f^2 & \text{for } d_f \leq d_{f,m} \\ u_{max,Nu} + (u_w - u_{max,Nu}) \frac{d_f - d_{f,m}}{d_{f,max} - d_{f,m}} & \text{for } d_{f,m} < d_f < d_{f,max} \\ u_w & \text{for } d_f = d_{f,max} \end{cases} \quad (6)$$

The stream wise velocity u_w at the interface in the wave peak and the local instantaneous film thickness d_f are determined using the LIF technique. Thereby u_w is approximated with the wave propagation velocity c_w which in turn is determined from a two point measurement using a cross correlation method reported for example in Al-Sibai (2005).

The temperature dependency of the fluorescence shows only a small influence on the signal height of the fluorescence emission. Increasing the temperature results in a slight decrease of the signal. Comparable behavior is shown by the fluorescence indicator Rhodamine 110 which is used by Sakakibara and Adrian (1999). At constant biacetyl concentration the fluorescence emission solely depends on the film thickness. With appropriate calibration of the measuring device this allows for an accurate measurement of the film thickness.

Before carrying out the experiments some preliminary model-based investigations were done to examine the influence of different temperature and velocity distributions on the phosphorescence signal decay. As a result it can be stated that the dependence of the signal M on temperature is significant. A given difference in the temperature distributions results in a difference of the signals with weak information loss. The influence of different velocity distributions on the phosphorescence decay shows a smaller sensitivity. The resulting signals for this calculation differ only marginally for short observation times of 1 ms in the simulated measurements. Therefore using an approximate velocity distribution in the evaluation procedure is sufficient as long as the residence time of excited biacetyl molecules within the observation volume is large compared to the measuring time. For further details see Schagen and Modigell (2006).

3. Experimental Design

3.1. Optical Measuring Technique

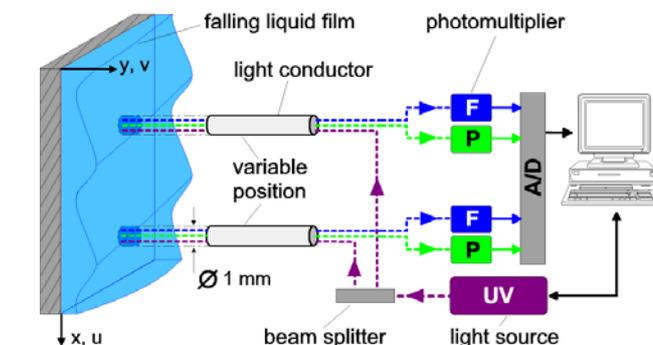


Fig. 3. Principle of simultaneous two point measurement.

To obtain information on the wave peak velocity u_w which is needed to characterize the wave properties, the measurement has to be performed at two points in film flow direction simultaneously. The emission of the dissolved and homogeneously distributed biacetyl is measured with four photo-multipliers (Hamamatsu Photonics K.K., Japan). Two of the photo-multipliers

measure the phosphorescence to get the temperature profile in the liquid film and the other two measure the fluorescence to get the local film thickness. To separate the information containing indicator emission from the (reflected) excitation light they are equipped with optical edge filters (Schott AG, Germany). For the separation of the phosphorescence edge filters GG 475 and for the separation of fluorescence OG 515 are used. Figure 4 shows the normalized spectra of excitation and luminescence emission of biacetyl measured with a LIMES-spectrometer (LTB GmbH, Germany).

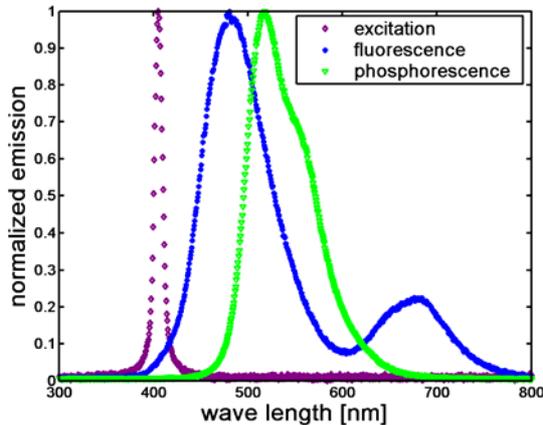


Fig. 4. Normalized emission spectra of excitation, fluorescence and phosphorescence.

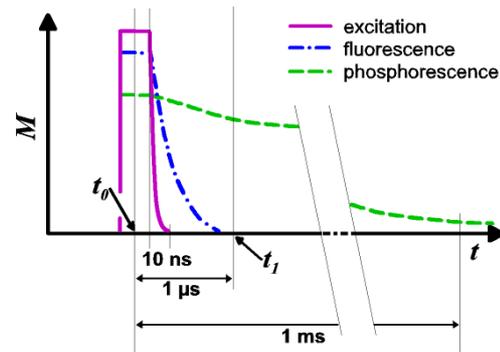


Fig. 5. Scheme of the time dependent behavior of excitation and luminescence emission.

A spectral separation of fluorescence and phosphorescence is not possible. Here the separation is based on by the different emission lifetimes. The fluorescence has a mean emission life time of about 3.6 ns whereas the mean emission lifetime of the phosphorescence is 231 μ s in oxygen free water at $\vartheta = 20$ °C. In Fig. 5 the procedure is shown schematically. The fluorescence is measured at the moment of excitation t_0 . After a delay time of 1 μ s the measurement of the phosphorescence is started at t_1 . The corruption of the fluorescence data by phosphorescence can be neglected, because the phosphorescence intensity is two orders of magnitude smaller than the fluorescence intensity in our measurements.

The analog signals of the photo-multipliers are converted to digital signals with a fast A/D-conversion card (Spectrum GmbH, Germany) with a frequency of 1 MHz per channel so that the temporal resolution of the intensity measurement is 1 μ s. The measuring duration after a single laser shot is about 1 ms. Different jitter of the laser and the measuring card were equalized with an external synchronizing clock and a pulse/delay generator (Quantum Composers Inc., USA). The remaining fluctuations in excitation intensity of the laser dye are measured with an additional photo-multiplier. In all measurements the indicator emission was corrected with the excitation fluctuations.

Liquid thickness measurements using a petri dish filled to different film heights have shown a linear dependence of fluorescence intensity on liquid film thickness in the range of $d_f = 0.7$ to 1.4 mm. The distance between the end of the light conductor and the bottom of the petri dish was 4 mm. This is the same distance as in the falling film experiments between the light conductors and the bottom plate of the evaporator. Assuming the same linearity in the falling film experiments the fluorescence measurements are evaluated on the basis of the determined dependance on d_f . According to the thickness measurement at the petri dish the error in film thickness is 2.1 % standard deviation in respect to the mean value of 1 mm film thickness.

With the specified measuring device it is possible to simultaneously obtain information about film thickness and temperature distribution every 20 ms. The phosphorescence signal which is used to reconstruct the temperature distribution has a temporal resolution of 1 μ s.

3.2. Falling Liquid Film Setup

The experimental setup for the temperature distribution measurement in a falling liquid film is shown schematically in Fig. 6. The main reservoir contains demineralized water degassed with purified nitrogen 5.0. OxiSorb[®] (Messer-Griesheim GmbH, Germany) is used to remove traces of moisture, oxygen and hydrocarbons from the nitrogen gas supply. The mechanism is a chemisorption of the impurities with reactive chromium compounds. The dissolved oxygen is stripped from the water by nitrogen bubbles. The oxygen concentration is reduced down to 10^{-6} mol/m³ which is the lower bound of the indicator sensitivity range for measurement of concentration distributions, see Schagen and Modigell (2005). After degasification the luminescence indicator biacetyl is added in a concentration of 11.4 mol/m³. In this concentration biacetyl does not change the physical properties of the liquid significantly. A measurement of the surface tension of the aqueous biacetyl solution with a du Nuoy tensiometer results in a value of $72.5 \cdot 10^{-3}$ N/m. The surface tension of pure water is $72.75 \cdot 10^{-3}$ N/m at 20 °C.

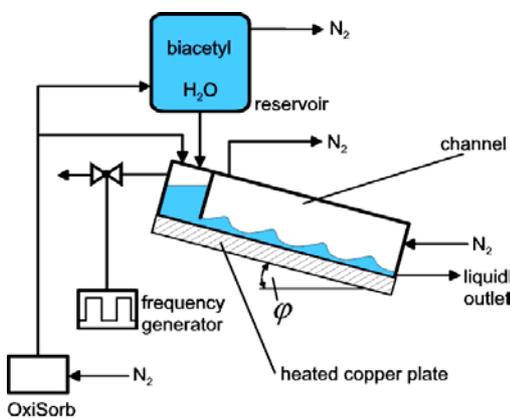


Fig. 6. Scheme of the experimental setup.

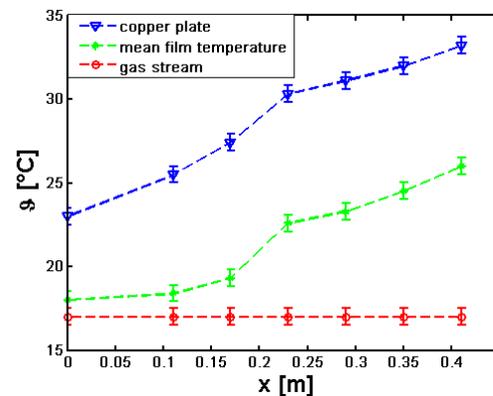


Fig. 7. Surface temperature of the copper plate, mean film temperature and gas stream temperature during the experiment.

The conditioned liquid flows out of the main reservoir into the film device, which can be inclined relative to the horizontal plane in the range of $\varphi = 0$ to 60° . The liquid flows out of a storage chamber through a manually adjustable slit into the heating chamber with an overall length of $L = 630$ mm, a width of $W = 70$ mm and a height of $H = 30$ mm. With separate gas streams the storage and the main chamber are rinsed to form a nitrogen atmosphere above the liquid surfaces to prevent additional quenching of the phosphorescence by molecular oxygen. A magnetic valve with an adjustable control frequency is installed at the outlet of the storage chamber stream to excite the liquid in this chamber with pressure pulses. Thus the liquid forms a developing laminar-wavy flow in the evaporator.

The falling liquid film is heated from below using an electrically heated copper plate of 6 mm height, 630 mm length and 130 mm width. The copper plate can be heated up to a maximum temperature of $\vartheta_{w,max} = 60^\circ\text{C}$ if no liquid film flows down the plate. During the experiment the temperature of the copper plate increases from 23°C at the liquid inlet to 33.2°C at the position $x = 410$ mm as can be seen in Fig. 7. These measurements are used as an initial guess for the wall temperature in the evaluation procedure. An integral temperature of the liquid film was invasively measured with a thermocouple. The physical properties of the liquid are calculated with these temperatures and are assumed to be constant while evaluating the phosphorescence signals. For the evaluation point at $x = 230$ mm the temperature is $\vartheta = 22.6^\circ\text{C}$. The properties of water at this temperature are $\rho = 997.64$ kg/m³, $c_p = 4.181$ kJ/(kg K), $\lambda = 0.598$ W/(m K), $\eta = 0.95 \cdot 10^{-3}$ kg/(m s) and the Prandtl number is 6.66. The temperature of the counter-current gas stream remained constant at 17°C . All temperatures were measured with an accuracy of $\pm 0.5^\circ\text{C}$ (Ahlborn Therm

2250-1).

4. Experimental Data and Evaluation

The settings used during the experiments on the laminar-wavy liquid film flowing down the inclined and heated plane are summarized in table 1.

Table 1: Parameters of the experimental setup.

Design parameter	Name	Value
liquid side Reynolds number [-]	Re_l	126
gas side Reynolds number [-]	Re_g	200
inclination angle [°]	φ	2
liquid flow rate [l/h]	\dot{V}_l	32
gas flow rate [l/h]	\dot{V}_g	551
disturbance frequency [Hz]	f_d	2
initial liquid temperature [°C]	ϑ_0	18
Constant gas temperature [°C]	ϑ_g	17

4.1. Film Thickness and Wave Velocity

In Fig. 8 the film thickness relative to the mean film thickness versus time is depicted. The values were obtained from fluorescence measurements at position $x = 230$ mm. At this position the velocity distribution in flow direction can be approximated with the parabolic profile described by Eq. (5). The mean of fluorescence emission is based on 2000 data points measured in an interval of 40 s. This result constitutes the calibration value that corresponds to the mean film thickness predicted by Nusselt (1916) theory

$$d_{f,m} = \left(\frac{3 \nu^2 Re_l}{g \sin \varphi} \right)^{1/3} = 1.04 \cdot 10^{-3} \text{ m} \quad (7)$$

Experimental values of Brauer (1961) for vertical films and Al-Sibai (2005) for inclined wavy films confirm the relation of Nusselt for the film thickness.

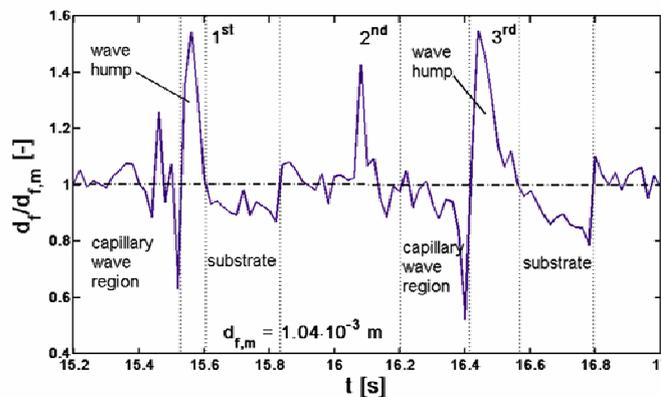


Fig. 8. Film contour at measuring point $x = 230$ mm for $Re_l = 126$.

Looking at the first and the third wave three characteristic regions of a single wave can be identified. The capillary wave region in front of the wave hump, which consists of the wave crest

and the wave back, and the substrate behind the wave back. The maximum height of the wave peaks with respect to the mean film thickness is about 55 %. The minimal film thickness with respect to the mean film thickness of about 40 % is located in front of the wave hump.

Analyzing the fluorescence data leads to the mean wave length $\lambda_w = 0.18$ m and the mean wave velocity $u_w = 0.4$ m/s. From a Fourier analysis the primary wave frequency can be determined as $f_w = 2$ Hz which corresponds to the excitation frequency. Higher order frequencies which can be found in the power spectrum result from the capillary waves in front of the main wave.

4.2. Temperature Distributions

The temperature distribution is obtained from the decay of phosphorescence intensity. Such a phosphorescence intensity decay curve is measured with a temporal resolution of 1 μ s. The reconstruction of the interesting temperature profile from the phosphorescence decay measurement is an inverse problem. To solve this problem it was formulated as an optimization task. As optimization algorithm an evolutionary algorithm was used. These algorithm are discussed extensively in the books of Rechenberg (1994) and Schwefel (1995). For the construction of a temperature profile the phosphorescence decay within ≈ 0.6 ms is used. The spatial resolution depends on the number of points to which the temperature distribution is numerically mapped in the evaluation procedure ($N = 25$). Therefore the spatial resolution is about 40 μ m in y-direction.

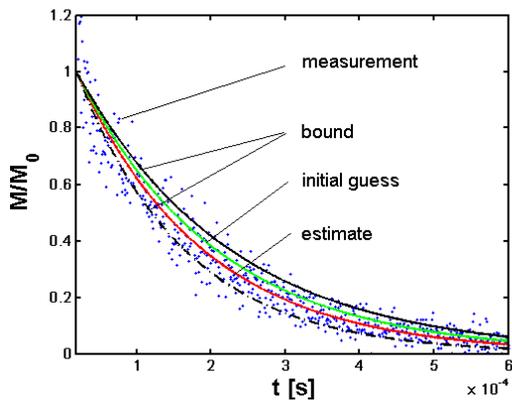


Fig. 9. Phosphorescence decay curve measured in the peak of the third wave in Fig. 14. Model based signals calculated with temperature bounds, the initial guess for the temperature distribution and the estimated temperature distribution, see Fig. 10.

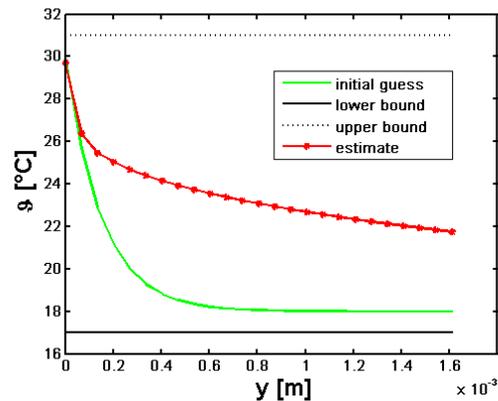


Fig. 10. Temperature constraints to restrict the solution space, initial guess and reconstructed temperature distribution from evaluation of the measured signal shown in Fig. 9.

The evaluation of the signal measured in the wave peak is described exemplarily. In Fig. 9 the noisy phosphorescence signal measured within the wave peak at $t = 16.44$ s is given. With the upper and lower temperature bounds, see Fig. 10, the region of possible solutions is confined. The resulting model-based signals are depicted in Fig. 9. The initial guess for the temperature distribution makes use of the wall temperature of $\vartheta_w = 30$ °C at the position $x = 230$ mm and the liquid inlet temperature, see Fig. 7. Although the initial guess is generated with an exponential model, this model was not used for evaluation. The estimated temperature profile shows a steep gradient at the wall and a non-vanishing gradient at the interface.

To confirm that the reconstructed temperature profile is an accurate fit to the experimental data, the mean relative deviations ε of the data from the calculated signals were determined according to

$$\varepsilon_{i,m} = \frac{1}{k} \sum_{j=1}^k \frac{M_i(t_j) - M_{\text{exp}}(t_j)}{M_i(t_j)} \quad (8)$$

with $i = 1$: estimate, 2: initial guess, 3: upper bound, 4: lower bound.

The mean of the relative deviations of the experimental data from the signal calculated with the estimate of the temperature distribution is $\varepsilon_{1,m} = -0.0097$. Further the mean relative deviations of the experimental data from the remaining signals were calculated. The mean relative deviations are $\varepsilon_{2,m} = 0.0946$ with respect to the initial guess, $\varepsilon_{3,m} = -0.362$ with respect to the upper bound (ϑ_u) and $\varepsilon_{4,m} = 0.159$ with respect to the lower bound (ϑ_l). Evidently the mean relative deviation $\varepsilon_{1,m}$ is one order of magnitude closer to zero than the value with respect to the initial guess $\varepsilon_{2,m}$. Thus the estimated temperature profile gives the best phosphorescence signal to fit the measured data.

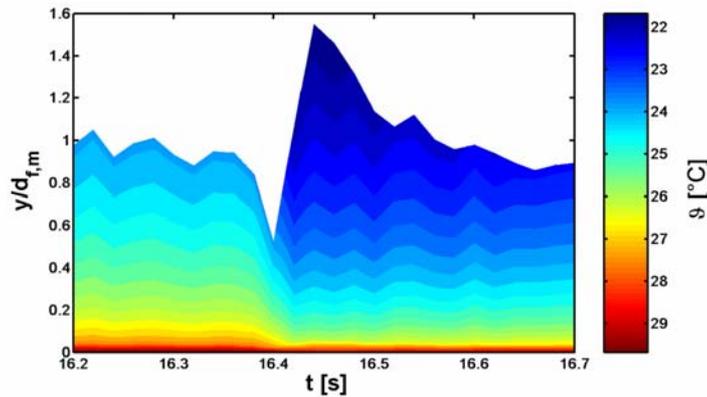


Fig. 11. Iso temperature lines along the wave at position $x = 230$ mm for $Re_l = 126$.

Evaluation of all phosphorescence signals obtained from the third wave in Fig. 8 leads to the temperature field shown in Fig. 11. It can be seen that the surface temperature as well as the temperature gradients in y -direction differ along the wave. In the wave crest and the wave back the temperature gradient is steeper than in the capillary wave region. The maximum change in the gradient along the wave can be localized in front of the wave peak. The wave hump, in which a large amount of mass with lower temperature is transported, flattens the temperature boundary layer of the substrate. The surface temperature in the wave crest and the wave back varies from 21.7 to 23 °C. In the capillary wave region a nearly constant temperature of 24 °C is reached.

4.3. Local Instantaneous Heat Transfer Coefficient

In investigations on heat transfer in falling liquid film evaporators or reactors often a constant local heat transfer coefficient is assumed. As a result of the proposed measurement method it can be shown that this assumption is a simplification especially in the case of a wavy film. The local heat transfer coefficient for the considered case is defined as

$$\alpha_{w,i} = - \frac{\lambda \frac{\partial \vartheta}{\partial y} \Big|_{y=0,d_f}}{\Delta \vartheta_{w,i}} \quad (9)$$

with the indices w and i denoting the wall and the interface respectively. Heat transfer is driven by the overall temperature difference, which is in the case of transfer from the wall to the liquid is defined as $\Delta \vartheta_w = \vartheta_w - \vartheta_i$. Looking at the transport from the liquid to the gas phase it is $\Delta \vartheta_i = \vartheta_i - \vartheta_g$, the latter being the gas temperature. In Fig. 12 the course of the local heat transfer coefficient is depicted for both cases normalized to the respective mean value.

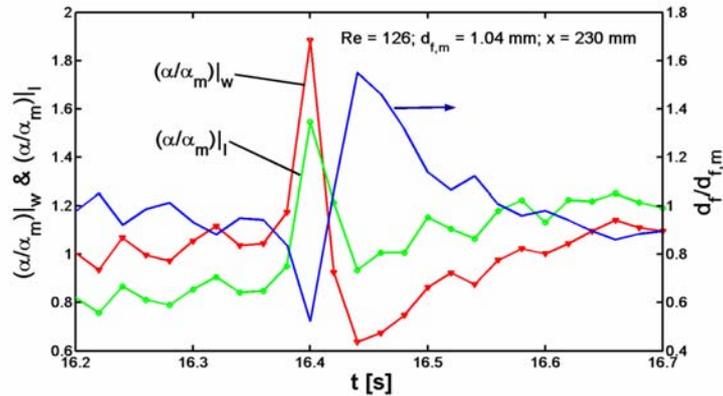


Fig. 12. Local heat transfer coefficient along the wave at position $x = 230$ mm.

The mean transfer coefficient at the heated wall is determined as $\alpha_{w,m} = 2190.5$ W/(m² K) and for the value at the interface $\alpha_{i,m} = 184.2$ W/(m² K) is obtained. Both curves of the local heat transfer coefficient show a significantly higher value in front of the wave and a minimum beneath the wave hump. After that the curves increase slowly to their mean values. This is in qualitative agreement with the experimental results of Al-Sibai et al. (2002). The peak of the transfer coefficients in front of the wave as a result of our experiments cannot be found in their experiments. Possibly it is caused by the different experimental setups. Al-Sibai et al. used an electrically heated thin foil (2 μ m) to realize a constant heat flux into a silicon oil film excited with 10 Hz to laminar-wavy flow, a Reynolds number of 14.5 and a Prandtl number of 10. Numerical simulations of Adomeit et al. (2000) for a Reynolds number of 50 and a Prandtl number of 1 are in good agreement with our experimental results, see Fig. 13. The course of the dimensionless local heat transfer coefficient is qualitatively the same. Especially the peak in front of the wave and the behavior beneath the wave is congruent.

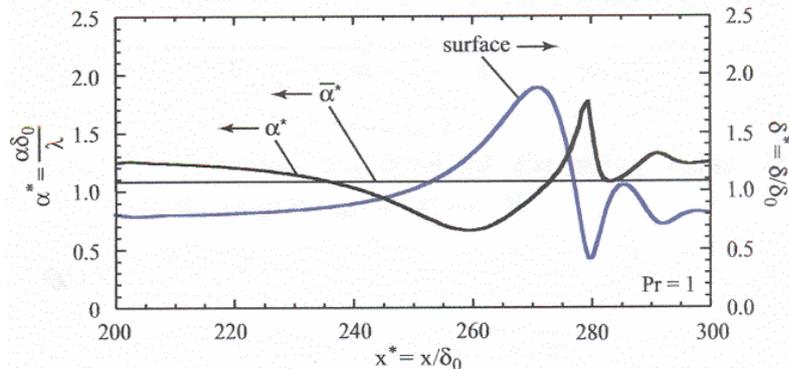


Fig. 13. Wave surface and instantaneous dimensionless local heat transfer coefficient α^* at $Re = 50$, taken from Adomeit et al. (2000).

5. Conclusion

A new measurement method for the determination of the temperature distribution with high spatial and temporal resolution in thin liquid films is presented. This method is based on the temperature dependent emission lifetime of an optical indicator. First results for the heat transport in a wavy falling liquid film flowing down a heated plane are presented exemplarily.

With the temperature profiles determined from measurements in a laminar-wavy falling liquid film the local heat transfer coefficients in the development of a solitary wave are calculated. The calculations show that the local heat transfer coefficient is not constant along the wave as it is often assumed. Here the maximum value is reached in front of the wave between the capillary wave

region and the wave crest. It can be concluded that enhancement of heat transfer in wavy films is dominated by the high frequent motion in the capillary wave region in front of the wave hump.

Further investigations of the kinetic phenomena covering single waves will be done for laminar-wavy falling liquid films flowing down a heated plane at different positions in flow direction varying Reynolds number and inclination angle of the evaporator. The results will be the basis for research of coupled heat and mass transfer mechanisms including chemical reactions in falling liquid films.

Acknowledgement -- The authors gratefully acknowledge the financial support of the Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Center (SFB) 540 "Model-based Experimental Analysis of Kinetic Phenomena in Fluid Multi-phase Reactive Systems".

Nomenclature

Latin symbols

c	specific heat capacity, J/(kg K)
c	wave propagation velocity, m/s
C	molar concentration, mol/m ³
d	thickness, diameter, m
f	frequency, 1/s
H	height of channel, m
I	intensity, W/m ²
K	constant device factor, V m/W
L	length of channel, m
M	measured phosphorescence, V
n	distribution of effective emission area, m ²
N	number of nodal points
Pr	Prandtl number = ν/κ
Re	Reynolds number = $\dot{V}/(\nu W)$
t	time, s
u	streamwise velocity, m/s
V	volume, m ³
W	width of channel, m
x	streamwise coordinate, m
y	normal coordinate, m

Greek symbols

α	heat transfer coefficient, W/(m ² K)
ε	relative deviation, bound
η	dynamic viscosity, kg/(m s)
φ	inclination angle, °
κ	thermal diffusivity, m ² /s
λ	thermal conductivity, W/(m K)
λ	wave length, m
ν	kinematic viscosity, m ² /s
ϑ	temperature, °C
ρ	density, kg/m ³
τ	decay constant, s

Subscripts

d	Disturbance
f	Film
g	Gas
l	liquid, lower bound
m	mean
ob	observation volume
u	upper bound
w	wave, wall

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