Motion and Evaporation of Shear-Driven Liquid Films in Turbulent Gases

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Abstract

Detailed measurements of wavy liquid films driven by the shear stress of turbulent air flow are obtained for different air temperatures, air velocities and flow rates of the liquid. The experimental conditions are chosen from characteristic data of liquid film flow in prefilming airblast atomizers and film vaporization employing combustors.

For the measurement of the local film thickness and film velocity a new optical instrument - based on the light absorption of the liquid - has been developed, which can be used at high temperatures with evaporation.

The measured data of the gas phase and the liquid film are compared with the results of a numerical code using a laminar as well as a turbulent model for the film flow and a standard numerical finite volume code for the gas phase.

The results utilizing the two models for the liquid film show that the film exhibits laminar rather than turbulent characteristics under a wide range of flow conditions. This is of considerable interest when heat is transferred across the film by heating or cooling of the wall. With this information the optical instrument can also be used to determine the local shear stress of the gas phase at the phase interface.

Using time averaged values for the thickness, the velocity and the roughness of the film the code leads to relatively accurate predictions of the interaction of the liquid film with the gas phase.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Physical Property</th>
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<tr>
<td>C</td>
<td></td>
<td>constant in log. law</td>
</tr>
<tr>
<td>( c_p )</td>
<td>J/kgK</td>
<td>specific heat</td>
</tr>
<tr>
<td>( l )</td>
<td>W/m²</td>
<td>light intensity</td>
</tr>
<tr>
<td>( h_{so} )</td>
<td>m</td>
<td>gap height without film</td>
</tr>
<tr>
<td>( h_{cal} )</td>
<td>m</td>
<td>calibration film thickness</td>
</tr>
<tr>
<td>( (h_{iw} - h_F) )</td>
<td>J/kg</td>
<td>latent heat for the evaporation</td>
</tr>
<tr>
<td>( H_F )</td>
<td>W/m</td>
<td>enthalpy flux of the liquid per unit breadth</td>
</tr>
<tr>
<td>( \bar{h}_F )</td>
<td>m</td>
<td>time averaged film thickness</td>
</tr>
<tr>
<td>( k_s )</td>
<td>m</td>
<td>equivalent sandgrain roughness</td>
</tr>
<tr>
<td>( k' )</td>
<td>1/m</td>
<td>absorption coefficient of the liquid</td>
</tr>
<tr>
<td>( \bar{m} )</td>
<td>kg/s</td>
<td>mass flux</td>
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<td>index of refraction</td>
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</tr>
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<tr>
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<td>film velocity</td>
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<tr>
<td>( \nu_{cal} )</td>
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<tr>
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<td>( \tau )</td>
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Indices

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<tr>
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<td>calibration</td>
</tr>
<tr>
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<td>gas</td>
</tr>
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<td>( R )</td>
<td>radiation</td>
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**Introduction**

The knowledge of the parameters influencing the heat and mass transfer of wavy liquid films driven by the shear of a turbulent air flow are of dominant interest in various practical engineering applications. In extending our earlier experimental and computational studies of prefilming airblast atomizers (Aigner and Wittig (1985),(1987), Sattelmayer and Wittig (1986),(1989), Sattelmayer (1985), Aigner (1986)) experimental and numerical tools for the study of two phase flows with wavy liquid films have been developed. At the Institute for Thermal Turbomachinery at the University of Karlsruhe these tools are also used for the evaluation of film vaporization in combustors and the flow in intake pipes of internal combustion engines.

Several publications (Lefebvre (1980), Wittig et al. (1984), Sattelmayer and Wittig (1989)) show, that in prefilming airblast atomizers (Fig. 1) the wavy liquid films are influencing the velocity of the gas phase and thereby the spray characteristics. In order to predict the spray characteristics of airblast atomizers at various flow rates of the liquid and at different running conditions of the engine, the pressure drop caused by the liquid film must be taken into account.

![Figure 1: Prefilming Airblast Atomizer (Sattelmayer and Wittig (1989))](image1)

Most of the previous investigations on prefilming airblast atomizers have been done at low temperatures. For the application of the correlations derived from these data for the prediction of the spray characteristics at the high temperature and high pressure conditions of gas turbines, the flow conditions of the gas at the atomizing edge must be known as well as the fuel temperatures, because the fuel properties are strongly varying with temperature. With this information the boundary conditions for a calculation of the motion and evaporation of the spray in combustors (Wittig et al. (1988)) are available.

At high temperatures the two phase flow inside the nozzle is characterized by a coupled heat and mass transfer at the liquid/gas interface (Fig. 2). Depending on the flow rates and temperatures of the gas and the liquid, different velocity profiles of the gas phase and of the liquid film are found. In addition, the temperature profiles of the gas and the liquid change locally, as well as the concentration profiles of the vapour. For different kinds of airblast atomizers the film can be heated only by the gas phase, or both by the gas phase and by the prefilming plate on which the film is flowing. Further problems appear in the correct description of the coupling conditions for the momentum, the heat and the mass transfer at the phase interface.

![Figure 2: Internal Flow of a Prefilming Airblast Atomizer](image2)

**Calculational Procedure**

The turbulent gas flow over the wavy liquid film and the film flow itself are intrinsically unstable (Sattelmayer (1985), Sattelmayer and Wittig (1989)). Therefore, an exact solution of the governing equations for momentum, heat and mass transfer in the liquid and the gas phase is not applicable for practical use. Although encouraging studies on special problems of this complex two phase flow are available (e.g. Jurman and McCready (1989), Sheintuch and Dukler (1989), Kuzan and Hanratty (1989)), these models cannot be applied for this investigation, because of the coupled heat and mass transfer and because of the unstable film waves.

However, as earlier studies are pointing out, reasonable results can be obtained using time averaged calculational procedures (Whalley (1987), Sattelmayer (1985), Sattelmayer and Wittig (1989)). The dominant parameter for these calculations is the shear stress at the interface of the gas and the liquid. Assuming constant shear stress at the interface and in the film and ne-
glecting gravity effects, two fundamental equations for the time averaged film velocity profile were employed: A turbulent profile developed by Wurz (1971)

\[
u_F^+ = \frac{1}{2k'\gamma_F^+} \left[ \frac{1}{\gamma_F^+} \left[ 1 + \left( \frac{1}{2\gamma_F^+} \right)^2 \right] + \frac{1}{k'} \ln \left( 2\gamma_F^+ \left( 1 + \left( \frac{1}{2\gamma_F^+} \right)^2 \right) \right) \right]
\]

and a laminar profile

\[
u_F^+ = y_F^+
\]

These two equations represent the two physical extremes for the time averaged film velocities at a given shear stress. Because of the fundamental interest of this approach only the calculational results of these two profiles are presented. The results of a third equation with a three-layer approach (Whalley (1987)), which gave results between the above two profiles are omitted. For a water film of a given shear stress of 80 N/m² and a volumetric liquid flow of \( V_F/B = 1 \text{ cm}^2/\text{s} \) the resulting velocity profiles are compared in Fig. 3.

![Figure 3: Comparison of a Laminar and a Turbulent Film Velocity Profile](image)

The turbulent profile results in a higher thickness of the film and a lower surface velocity. However, in practical use the differences in film thickness will be less than in Fig. 3 because the shear stress is increasing with the film thickness, leading to an increasing film velocity. Following the approach of Cohen and Hanratty (1968) and Sattelmayer and Wittig (1989) for the coupling between the liquid film and the gas phase, an equivalent sandgrain roughness approach is used:

\[
k_s = \psi_r \cdot 2 \cdot h_F
\]

Measuring the boundary layer of the turbulent air over various liquid films and measuring the film thickness Sattelmayer (1985) found this correlation of \( \psi_r \) to give the best results when using the sandgrain approach to get the velocity profile of the gas with the logarithmic law of the wall.

In this approach we take our numerical code TEFAC2D for turbulent elliptic flows with a standard \( k-\epsilon \) turbulence model to calculate the turbulent gas flow in the gap. However, for this application a parabolic code could be used as well. The numerical methods of these codes are described in several publications (Patankar (1980), Noll (1986), Bauer (1989)). A detailed description of the numerical method employed for the calculation of the two phase flow with evaporating wavy liquid films will be published soon. However, the present paper is concerned with the evaluation of the calculational procedure by a comparison with the measurements.

### Experimental Setup

For the evaluation of the theoretical procedure, measurements of the internal two phase flows were accomplished. Fig. 4 gives a detailed view of the test section, which has a primary cross section of 83 x 60 mm², converging to a cross section of 13 x 60 mm². With the prefilming plate for the liquid film along the centerline of the channel, two gaps of 4 mm height are formed.

![Figure 4: Testsection for Evaporating Liquid Films](image)

The liquid film is flowing onto the prefilming plate through two rows of holes with a diameter of 0.5 mm and a lateral spacing of 0.8 mm at each side of the plate. These holes are supplied with liquid by holes of 2.5 mm diameter inside the prefilming plate. If conditions with heat transfer from the wetted wall to liquid film are chosen, the liquid is only supplied to one side of the plate. Under these conditions the prefilming plate is heated by the flow in the second gap without film. Otherwise the film is supplied to both sides of the prefilming plate, in order to provide adiabatic conditions on the wetted wall.

The shear at the interface of the gas and the liquid is driving the liquid film to the atomization edge, where the film is disintegrating into single droplets. Because of the fundamental nature of this investigation the length of the test section is much longer...
than in practical airblast atomizers. Thus the two phase flow can be examined at fully developed flow conditions. For the analysis of the liquid film, there are five locations with windows for the optical film thickness and film velocity measurements. These windows can be exchanged by covers containing probes with pitot tubes and thermocouples for the gas phase. The starting positions of the film can be varied as well as the draining positions and the positions of the optical instrument for the liquid film by exchanging the single modules of the prefilming plate. To remove instabilities between the modules and to improve the wetting of the surface the prefilming plate was roughened by a sand-blast unit over a range of 50 mm breadth. Thus side wall effects are reduced as well as discontinuities.

Although the test section is designed for air temperatures of 973 K and pressures of 10 bar, this first investigation is only concerned with ambient pressures and with temperatures up to 573 K.

Measurement Techniques and Diagnostics

In the test section, the properties of both the gas and the liquid phase have to be determined. The velocities and the temperatures of the gas phase were measured using pitot-tubes of 0.6 mm outside diameter with integrated thermocouples of 0.25 mm diameter. Because of the specific design conditions, the measuring positions of the velocity and temperature profiles were 10 mm ahead of the measuring positions of film thickness and velocity shown in Fig. 4. The y-positions of the profiles measured were corrected by the method of Mc Millan (1957) (Sattelmayer (1985)). The temperatures of the prefilming plate were determined with thermocouples of 0.25 mm diameter, which were soldered into the surface before roughening the surface with the sand-blast unit.

For the study of the film flow, an optical instrument based on the light absorption in the liquid was used. As originally shown by Sill (1982), Sattelmayer (1985) and Sattelmayer et al. (1987), with this instrument the local film thickness can be determined quite well. In comparison with other methods using the variation of the conductivity or the capacitance with film thickness this instrument has a very high local resolution because the light can be focussed to 80 microns and less. Thus this instrument can determine the structure of wavy films with very short wavelengths as they appear at high gas velocities. In our later work this technique could be improved to determine in addition the surface velocity of the film. Fig. 5 shows the experimental setup of the film thickness and film velocity measuring technique.

The beam of a laser is split into two measuring beams $I_1$ and $I_2$, a reference beam $I_o$, to determine the laser light intensity and a calibration beam $I_{cal}$ to determine the absorption coefficient with a film of defined thickness. The measuring beams are passing the liquid film through a scattering window, which is reducing interferences and influences of different angles of light coupling into the fibre of the detector. Measuring the film thickness the intensities $I_o$ and $I_{cal}$ are used in addition to one measuring intensity. With $I_o$ and $I_{cal}$ the absorption coefficient can be determined:

$$ k' = -\frac{1}{k_{cal}} \ln \frac{I_{cal}}{I_o} \quad (4) $$

resulting in the film thickness applying the following equation:

$$ h_F = -\frac{1}{k'} \ln \frac{I}{I_o} \quad (5) $$

If the instrument is used to determine the surface velocity of the film, only the measuring intensities $I_1$ and $I_2$ are of importance. The two beams are focussed on the film with a distance of 5 mm. Pulsed colouring of the liquid is producing two correlating signals, which can be transformed into film velocities by statistical methods. Methylene blue or colour from food industry were used to colour the liquid. Because of the high absorption coefficient of these colours, only a negligible mass flux of colour was needed, which was not influencing the film flow.

Sill (1982) and Sattelmayer (1985) used this setup to measure the film thickness under cold conditions with negligible evaporation. Thus they could adapt the measuring range of the film thickness by colouring the liquid in order to get the matching absorption coefficient. Of course, at high temperatures with evaporation the colouring of the liquid cannot be used, because the concentration of the colour is changing under these conditions.

Fig. 6 shows that this problem can be solved by using an infrared light source.
Using infrared light, the absorption in the film is high enough to determine the thickness without colouring the liquid. In the new instrument two superposed He-Ne laser wavelengths are used, with the 1523 nm line for measuring the film thickness and the 633 nm line to adjust the optics. Since the index of refraction of liquid water is almost identical for both laser wavelengths (n_{633\text{nm}} = 1.33; n_{1523\text{nm}} = 1.32), the red laser beam can be used to measure the light losses by reflection from the wavy surface of the film. Additionally, the light losses by scattering from droplets in the gap and losses by the coupling of the light into the fibres of the detector can be estimated.

Fig. 7 shows the optical film thickness measuring instrument for evaporating and condensing liquids. The instrument consists of a sending, a focussing and a receiving system. In the sending optics the red and the infrared beam are superposed with the aid of a beam splitter and then enlarged to get a better focus at the film. The beams are chopped with a rotating mirror. This provides a reference signal to determine the laser light intensity. The enlarged measuring beam is focussed on the film and then coupled into a second glass fibre.

In the receiving system the reference and measuring intensities are combined again and then split into the red and infrared wavelength with the help of an interference filter. A Si-Detector is used for the red and a Ge-Detector for the infrared light. The signals of the detectors are received by a transient recorder as well as the positions of the chopper. These signals are sent to a personal computer, which determines the film thickness.

Using only one detector to measure the red and the infrared light intensities and chopping the beams this instrument is independent from drifts in the sensitivity of the detectors and the laser intensity. Additionally, a third detector in the sending system is measuring the ripple of the infrared laser, because the available infrared lasers often show considerable ripple with high frequencies.

Results

For first tests of the new technique to determine the surface velocities of the film the test section described by Sattelmayer (1985) was used at cold conditions of the air. A gap height of 4.3 mm was examined, in order to provide fully developed flow at the measuring position of the film velocity and thickness.

Fig. 8 gives a comparison of the measured (see also Sattelmayer (1985)) and the calculated film thickness if turbulent film flow is assumed. The assumption of a turbulent film leads to a correct trend for the calculated film thickness. Nevertheless, the calculated values are too high for all gas velocities and liquid flow rates. Assuming a laminar profile for the film velocity, the measured and calculated data fit much better (Fig. 9), however, at high flow rates of the liquid the calculation shows increasing differences, indicating that the film might not be fully laminar in this region.

The measured velocities at the film surface in Fig. 10 emphasize the assumption that the film is almost laminar. There is a good agreement of the numerical and experimental results for the assumption of the laminar profiles.

At high liquid flow rates the measured film velocities suddenly are much higher than the calculated values. In this flow regime the waves of the film are breaking and droplets are torn off the film. Under these conditions the film surface velocity cannot be determined, because these disturbances are moving at a higher velocity than the film. However, the position where the measured velocities are rising very quickly can be used as a criterion to define the stability range of the film flow.

All these studies at gas velocities from 30 to 120 m/s indicate that the liquid film flow inside an airblast nozzle can be considered to be approximately laminar, if the liquid flow rate is not outside the range of stability. The wavyness of the film is not...
inducing significant turbulence into the film. This is of considerable interest if the heat transfer to the film has to be considered. Nevertheless the influence of the film flow rate on the pressure drop can be predicted at both gas temperatures.

![Figure 8: Film Thickness at Fully Developed Flow (Assuming a Turbulent Film)](image)

![Figure 9: Film Thickness at Fully Developed Flow (Assuming a Laminar Film)](image)

Based on these results measurements were performed at elevated temperatures to test the applicability of the numerical code for the description of two phase flows. For these experiments the new testsection shown in Fig. 4 was used. In order to provide adiabatic conditions for the film, the prefilming plate was wetted at both sides. Characteristic results from measuring plane 4 are shown in Fig. 11. They illustrate that the velocity and temperature profiles in the gap can be calculated quite well. As the test section was not insulated during these studies the temperature of the top wall was about 453 K. This was used in the numerical predictions as a boundary condition at the top wall. The coordinate of the grid point adjacent to the wall was optimized to be within $20 < y^+ < 40$.

The results for the pressure drops between measuring point 1, which is positioned at $x = 0$ where the gap is starting to be parallel, and the other measuring points in the gap are shown in Fig. 12. Several flow rates of the liquid and two different gas temperatures are examined. While the pressure drop at low temperatures and evaporation rates can be predicted quite well, the differences between the numerical and the experimental results are increasing at elevated temperatures. Nevertheless the influence of the film flow rate on the pressure drop can be predicted at both gas temperatures.

![Figure 10: Film Surface Velocities at Fully Developed Flow](image)

![Figure 11: Measured and Calculated Gas Velocities and Temperatures](image)

A very significant test for the predicted interaction of the gas phase and the evaporating wavy liquid film can be obtained by comparing the measured and calculated thickness and velocity of the film.

To determine the primary light intensity $I_p$ for the film thickness measurements at elevated temperatures, an offset volume flux of the film flow of $0.09 \text{cm}^2/\text{s}$ was necessary for cooling the
glass of the detector in the prefilming plate. As Figs. 13 and 14 with the data in plane 4 show, the differences between the measured and calculated film thicknesses and film velocities are acceptable. At high flow rates of liquid the measured velocities are showing the same characteristics as at cold conditions (Fig. 10): the film flow is not in the range of stability at this high flow rates. At low flow rates the experimental and numerical results for the film thicknesses and velocities agree quite well. Further investigations will have to examine if the increasing differences at elevated flow rates are an effect of the numerical code for the turbulent gas phase and the liquid film, or if the structure of the film is changing significantly at higher temperatures, so that the correlation of \( \psi_r \) would have to be modified. Before this can be done, a series of film thickness measurements at various gas temperatures and velocities and with various liquids will be necessary. In spite of the minor differences we feel that the numerical code can be used in practical applications.

Figure 12: Pressure Drop in the Gap for Inlet Gas Temperatures of 307 K and 573 K

Figure 13: Experimental and Numerical Results of the Film Thickness in Plane 4

Figure 14: Experimental and Numerical Results of the Film Surface Velocity in Plane 4

Conclusions

The behavior of wavy liquid films can be described with acceptable accuracy by employing time averaged velocity profiles of the film. Comparing measured time averaged film thicknesses and film surface velocities with numerical results of a laminar and a turbulent velocity profile for the film, the film flow was found to be almost laminar within the range of stability of the film. The turbulent air and the wavyness of the film is not inducing significant turbulence into the film. Using a standard numerical code for the turbulent gas phase and a laminar profile for the film velocity the interaction of the film and the gas phase can be estimated at cold conditions as well as at high temperature conditions. The developed optical film thickness and film velocity measuring instrument is a very useful tool to examine the effects at the interface between the gas and the liquid.

Acknowledgements

The present study was supported by a grant from the SFB 167 (High intensity combustors) of the Deutsche Forschungsgemeinschaft.

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