

Simultaneous Measure of Thickness and Temperature of an Infrared Semi-Transparent Layer

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Abstract

A novel thermographic techniques is proposed to measure simultaneously the thickness and the temperature of a layer that is semi-transparent to infrared radiations. The layer may be a thin solid or liquid film, like in the presented experiments, but the technique can be also used with minor modifications to a suspension of particles or droplets or a solution of different fluids. The technique can be applied when the measured layer reaches a minimum thickness such to be detected by an infrared sensor, like a camera, but it is not too thick to become totally opaque in the sensor wavelength range. These limits depend on the fluid investigated, on the precision of the measured temperatures, and on the accepted accuracy of the results. In the present work, we illustrate the working principles of the technique developed in a real situation, and present preliminary results on a new application.

Introduction

The development of techniques to measure the thickness and the temperature of a liquid film is an interesting topic for many two-phase flow studies. Various methods based on different physical principles have been proposed in the literature depending on the range of thickness investigated, fluid properties, wall material, and interface properties, many of them are able to measure the two properties by independent techniques or instruments [1, 2], more rarely by the same instrument [3]. We present here an original technique aimed at measuring the temperature and the thickness of a film, by a unique thermographic imaging device with a relatively simple set-up.

Theoretical development

The proposed technique starts from the observation that when measuring with an IR camera the temperature of a film, whose thickness makes it semi-transparent to IR radiations, the measured temperature is a weighted average between the film and the background temperatures, where the background is partially attenuated by the thin film depending on the film thickness and optical properties. In a typical application for direct measurement of layer temperature, the residual IR background visibility is an unwanted signal contribution. Even when the background temperature is known, the detected signal is influenced by both the film's temperature and thickness. Consequently, neither value can be accurately measured.

By a simplified application of Beer-Lambert's law, with an appropriate average absorption coefficient ζ_F of the film in the waveband of interest, when omitting some instrument constants, and neglecting the reflections, the film transmissivity and emissivity can be written as:

$$\text{transmissivity} \quad \tau_F = \exp(-\zeta_F \cdot L_F) \quad (1)$$

$$\text{emissivity} \quad \varepsilon_F = 1 - \tau_F \quad (2)$$

and the expression for the measured temperature can be derived as:

$$T_{\text{Measured}} = (\varepsilon_{BG} \cdot T_{BG}^4 \cdot \tau_F + \varepsilon_F \cdot T_F^4)^{0.25} \quad (3)$$

It shows that the measured temperature is a function of the film temperature T_F , of its thickness L_F , and of the other physical parameters involved: the background temperature T_{BG} , the film absorption coefficient ζ_F . Since two variables are unknown, at least two equations are needed to calculate them: this can be obtained by changing one parameter in the last equation. In the present work, the chosen variable parameter is the background temperature T_{BG} ; the use of different absorption coefficients may also be achieved by using cameras with different spectral ranges or appropriate spectral filtering. A more detailed calculation including some parameter omitted here can be found in [4] and [5].

The proposed technique was developed and tested on a water film of known variable thickness and homogeneous temperature, formed between two sapphire windows which are highly transparent to the IR radiation. As mentioned, two different background surfaces are used, two plates of high emissivity and known homogeneous temperatures T_{BG1} and T_{BG2} , mounted on a rail to easily switch them behind the film.

In the equations, as well in the figures and plots, the two background temperature are represented by the two colours blue and red, to remind they are respectively a cold and hot surface, while the film properties T_F and L_F are marked by the green colour.

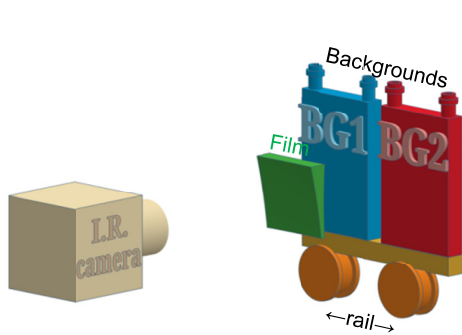


Figure 1. Scheme of the Twin Background set-up. Not shown the two windows enclosing the film are.

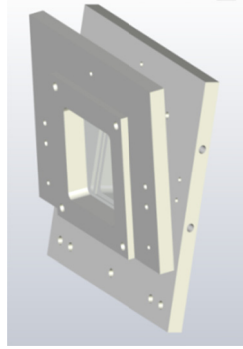


Figure 2. The windows with support.

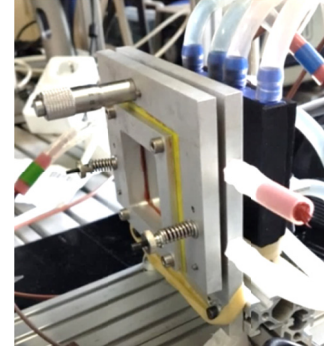


Figure 3. The real window support.

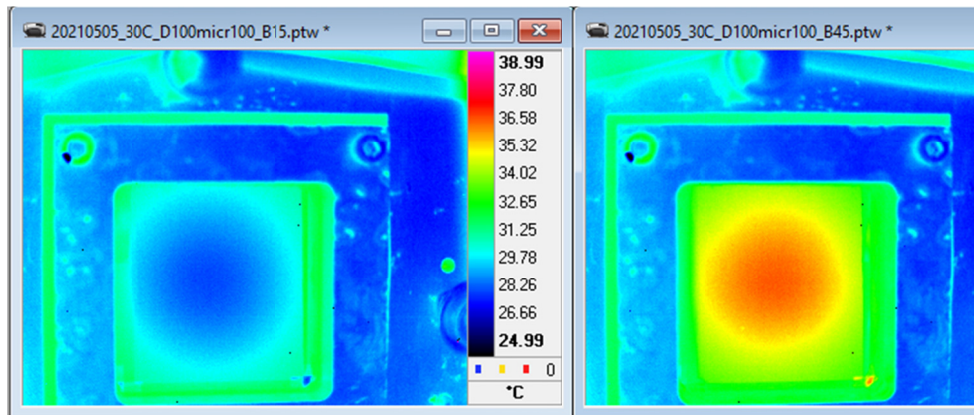


Figure 4. IR temperature measured with the two backgrounds at 15° and 45°, and a 100 μ m water film at 30°C with a 40 μ m concavity. Also visible the windows frames and support.

The temperatures measured in the two different configurations, also considering $\epsilon_{BG} = 1$, can be written as:

$$T_{Measured1}^4 = T_{BG1}^4 \cdot \tau_F + \epsilon_F \cdot T_F^4 \quad (4)$$

$$T_{Measured2}^4 = T_{BG2}^4 \cdot \tau_F + \epsilon_F \cdot T_F^4 \quad (5)$$

By subtraction, the contribution of the film in two signals is annulated, and the only difference between the two backgrounds is left, attenuated by the film thickness. It is so possible to isolate and solve for the Film transmissivity term τ_F , independently from the film temperature.

$$T_{Measured2}^4 - T_{Measured1}^4 = T_{BG2}^4 \cdot \tau_F + \epsilon_F T_F^4 - T_{BG1}^4 \cdot \tau_F - \epsilon_F T_F^4 = (T_{BG2}^4 - T_{BG1}^4) \cdot \tau_F \quad (6)$$

From τ_F the film thickness L_F can be derived from its known optical properties, and then also the film temperature T_F can be solved. These equations suggested to name this new technique as TBS, Twin Background Subtraction. The attenuation from the film should be sufficient to be not negligible, nor excessive to avoid total attenuation. The range of thickness that can be measured depends on the combination of the medium attenuation properties, on the IR bandwidth of the detector and on its accuracy [6]. For example with water, in the MWIR range (3.6-5.1 μ m) the measurable thickness results between 10 and 300 μ m.

The uncertainty of the technique was estimated theoretically with some simple assumptions. The accuracy of the two background temperatures is considered sufficiently good accurate to be neglected, as well as negligible are considered the uncertainties on the emissivity ϵ_{BG1} , and ϵ_{BG2} . The uncertainty of the windows transmissivity and extinction were estimated 5%, and the uncertainty of the measured apparent temperature T_{M1} was T_{M2} considered 0.5K. These uncertainties propagates in the calculated thickness and temperature of the film. Results are

reported in the following figures, where the film thickness is normalised by the length $L_0 = 1/\xi$, so when $L/L_0=3$ the attenuation is 95%.

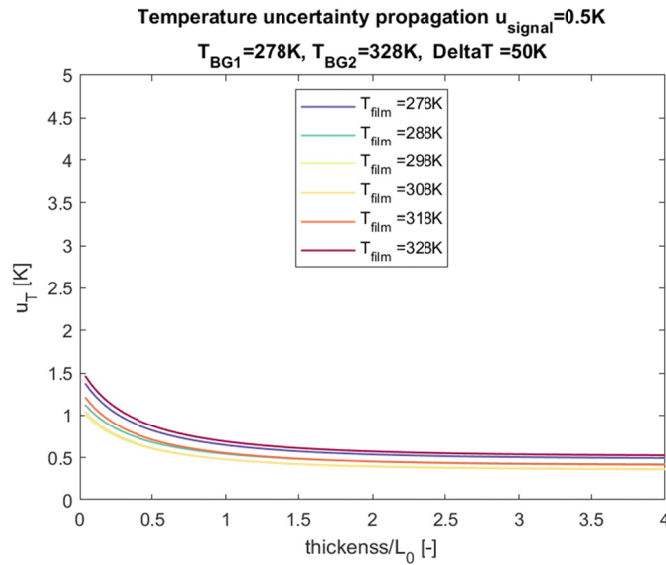


Figure 5. Uncertainties propagation on measured film Temperature T_F with a temperature background difference of 50 K. Film thickness is normalised by the length L_0

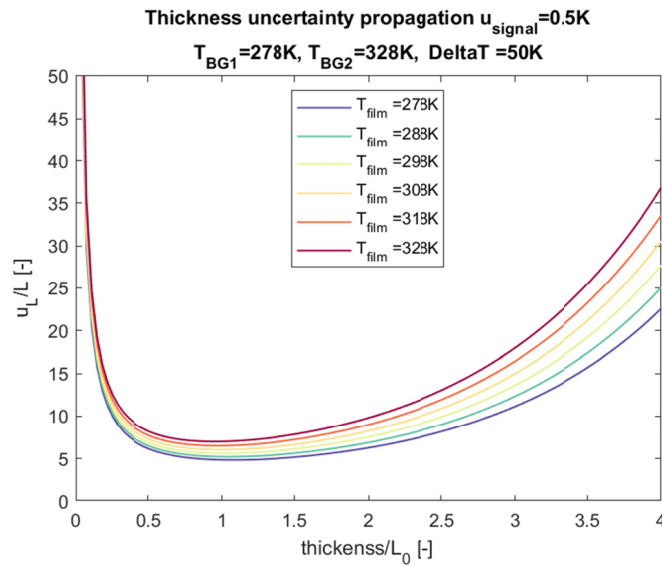


Figure 6. Uncertainties propagation on measured film Thickness L_F with a temperature background difference of 50 K. Film thickness is normalised by the length L_0

The calculated film temperature shows a maximum when the film thickness is minimal since without attenuation the error goes to infinite. On the other side, when the thickness completely attenuates the background, the film temperature is measured with no background influence, so it becomes a simple thermographic measure with its characteristic error due to the instrument used.

The calculated film thickness shows a flat minimum in the range $0.5 < L/L_0 < 2$, while for a very thin or a very thick thickness the error goes to infinite.

The equations (1) (2) (6) can be used to express the measured temperatures T_{meas1} and T_{meas2} as a function of the film temperature T_F and thickness L_F or L/L_0 , and of the background temperatures. An example of the graphic results is reported in the following figure, where the fixed parameters are $T_{BG1} = 10^\circ\text{C}$ and $T_{BG2} = 70^\circ\text{C}$. The measured temperatures are reported with step intervals of 10°C .

The point of intersection of the two lines corresponding to T_{meas1} and T_{meas2} gives the calculated values of the film properties; two examples are reported with square and circular markers.

Note that in reality, it must be always $T_{meas1} < T_{film} < T_{meas2}$, if it is found that $T_{meas1} > T_{meas2}$, which could happen because of measurement errors, the calculated T_{film} would be an imaginary number.

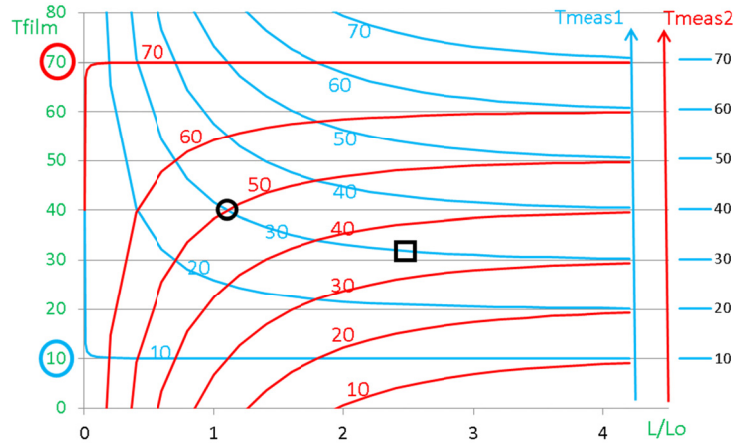


Figure 7. Measured temperatures function of film temperature T_{film} and film normalized thickness L/L_0 , with $T_{BG1}=10^{\circ}C$ and $T_{BG2}=70^{\circ}C$. Examples: \circ) $T_{meas1}=30$, $T_{meas2}=50 \rightarrow T_{film}=40$, $L/L_0=1.1$. \square) $T_{meas1}=30$, $T_{meas2}=35 \rightarrow T_{film}=32$, $L/L_0=2.4$.

For very thick films, with $L/L_0 > 4$, the measured temperatures converge asymptotically to the film temperature T_{film} . The best accuracy is obtained when the two lines T_{meas1} and T_{meas2} cross each-other perpendicularly, that is when $L/L_0=0.69$ and the attenuation is 50%, where is maximized the measure-over-error ratio both for emission and transmission from the film.

A solution is found also when T_{film} is not between the two background temperatures, as shown in the following figure, but in such a situation the measured temperature lines cross each-other with a narrow angle, thus increasing the errors in the estimated results.

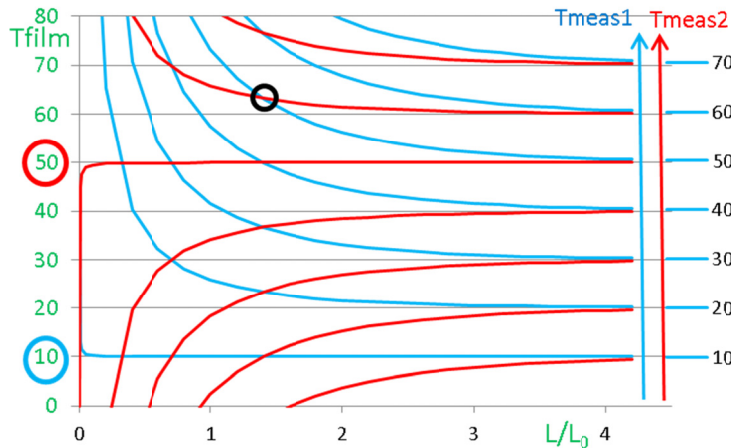


Figure 8. Case with $T_{film} > T_{BG2}$. Example with $T_{BG1}=10^{\circ}C$ and $T_{BG2}=50^{\circ}C$. Examples: \circ) $T_{meas1}=50$, $T_{meas2}=60 \rightarrow T_{film}=63$, $L/L_0=1.3$. Note the unfavourable intersection.

Experimental validation

The ideal fluid for the presented technique reaches full absorption above the maximum thickness to be measured, and a profile that can be easily fitted with the ideal one-term exponential, for easy inversion of the equations. This is found when the absorption or transmission spectrum profile is nearly constant in the bandwidth of interest, so the fluid behaves as a grey body. If it is not the case, the fluid is “coloured”, and the ratio between the real and the one-term decay is a known monotonic function, so the thickness calculation is still possible with a correction. As an alternative, the set of equations (1) (2) (6) can be solved for the unknown temperature and transmittance, and only at a later stage the film thickness is calculated.

For the first set of experiment to develop the technique, the fluid chosen was water after a comparison with other fluids. The following figure shows the transmittance spectrum of water in the infrared region. Water is a good fluid

in the range 3.6-5.1 μm (that of the used Flir Titanium 540M IR camera) because of its sufficiently flat profile, and may still be acceptable in the broader range of 3-5 μm .

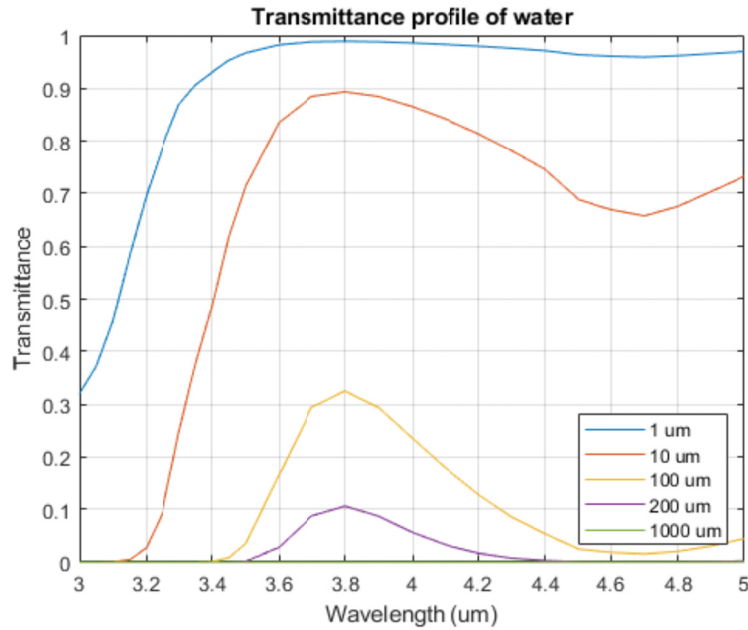


Figure 9. Transmittance spectrum of water in the infrared region.

Figure 10 reports the absorption coefficient of water and some fluids evaluated for the experiments, in the desired bandwidth 3-5 μm , calculated with the spectroscopic data from [7], while Figure 11 shows the difference between this calculated coefficient for water and its ideal one-term exponential expression.

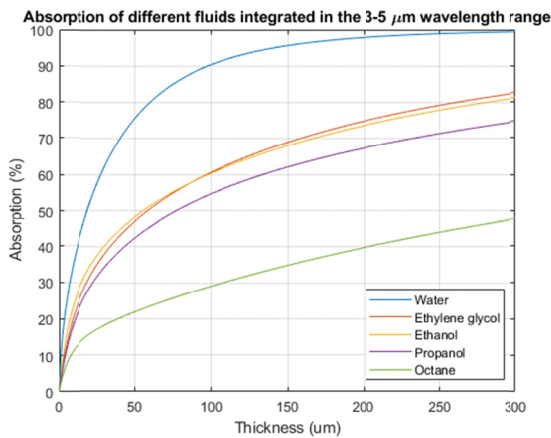


Figure 10. Different radiation absorption profiles of different fluids. Range 3-5 μm .

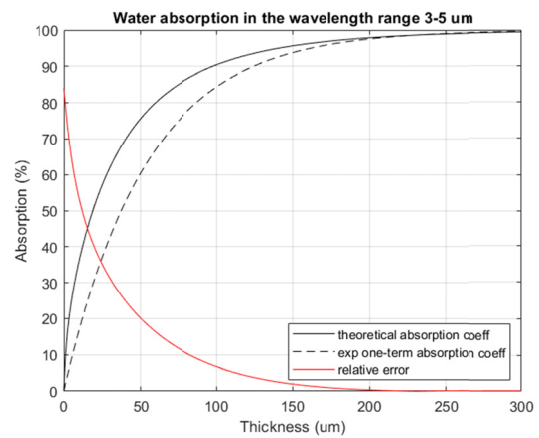


Figure 11. Radiation absorption of water difference between the actual theoretical curve and the one-term exponential. Range 3-5 μm

As introduced in the previous paragraph, the film generated to develop the technique is contained in between the two sapphire plates in a wedge shape. Depending on the window's distance on one side, the shape of the wedge film can be selected. The film presents a concavity at the centre, due to a manufacturing convexity of the two sapphire plates being not perfectly planar, hence causing a difference between the edge of the film and the centre of 40 μm . The following graphs show the result from three different tests. The first column shows a scheme of the film shape: the bottom film thickness is fixed at 100 microns, while the top thickness can be set from 0 to 500 μm ; the other two columns show the measured thickness and temperature presented as functions of the XY pixel coordinates, corresponding to the 40*40 mm^2 window.

The first row presents the results with the film temperature T_f set at 15 $^\circ\text{C}$ and the top film thickness set at the minimum possible, which is reached when the two windows get in contact due to their convexity. Around the contact region, where the film is very thin, both temperature and thickness results show high variation, or impossible results, due to the experimental errors leading to null denominator or negative logarithm arguments. Where the film is thicker than 10+20 μm , the measured thickness and temperatures give more realistic results.

The second row presents the results with the film temperature T_F set at 30°C, and the top film thickness set at 100 μm as the bottom; the minimum thickness is about 60 μm at the concavity, that is now centred. In this case, all measurements are corresponding to the reality, showing good accuracy and very fine precision.

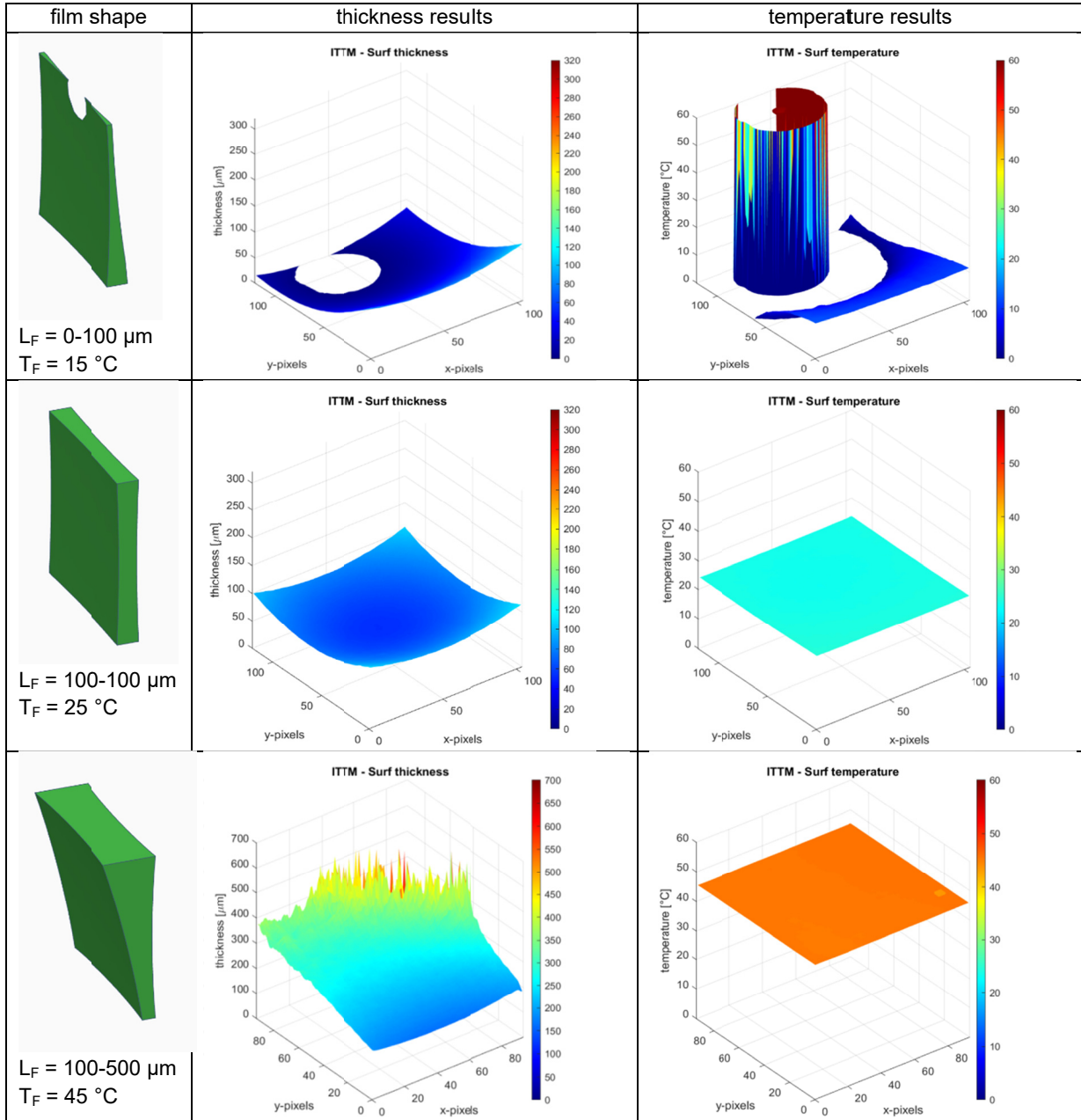


Figure 12. Results on a water wedge-shaped film, with different thickness and a 40 μm concavity, set at different temperatures, measured with the two backgrounds at 15° and 45°.

The third row presents the results with the film temperature T_F set at 45°C, and the top film thickness set at 350 μm . The thickness results are accurate up to 300 μm , then the attenuation is too high and noise dominates, due most probably to the too low bit resolution of the IR images, together with the reduced relative accuracy. On the contrary, the temperature measures are nearly perfect, since the film becomes so thick that can be considered fully opaque, and the residual signals from the background become negligible.

As an additional test, for the 100-100 μm film with central concavity, the following figure compares the thickness measured at each corresponding pixel by the twin techniques and by a classical optical light absorption technique, where water containing black ink was captured by a visible spectrum camera. The results present a very good agreement between the two measurements.

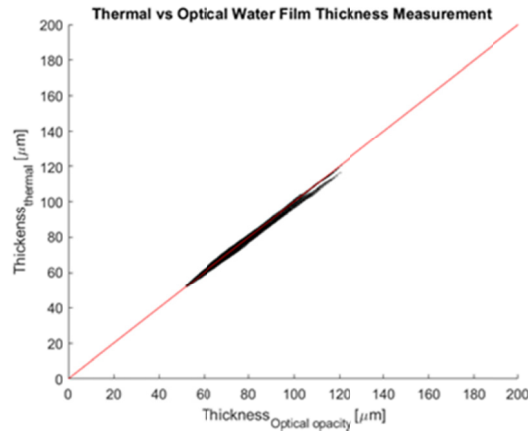


Figure 13. Thickness thermal results against optical results

Application to a tubular film

After proper calibration, the technique proved to be reliable, accurate, and with good potential for further development with different configurations. The following example shows the first development of the technique, used to study the liquid film formed in a 3 mm capillary tube with a two-phase flow formed in microgravity, tested in a parabolic flight campaign organised by the European Space Agency.

Thanks to an IR mirror, the hardware allows simultaneous acquisition with the two backgrounds, recorded on the same camera. The positioning is shown in the next figure, the tubular layer is supposed symmetric.

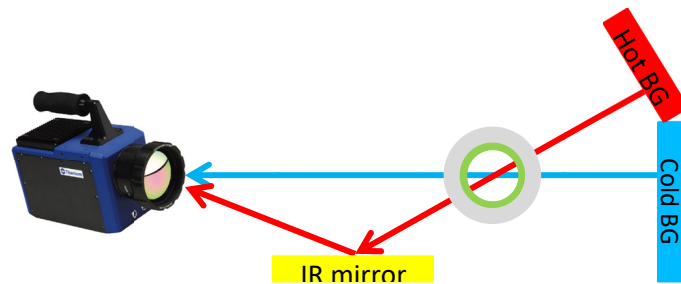


Figure 14. Set-up for measurements of the liquid layer around a bubble in a capillary tube.

The liquid used is ethanol, it required some algorithm modification, a purposely done attenuation calibration and its interpolation with a three terms exponential function. The measurable range extends to 700 µm total, the sum of two 350 µm symmetric layers.

The figure below shows an example of the results, it is a single frame from a 15 minutes movie at 100 Hz.

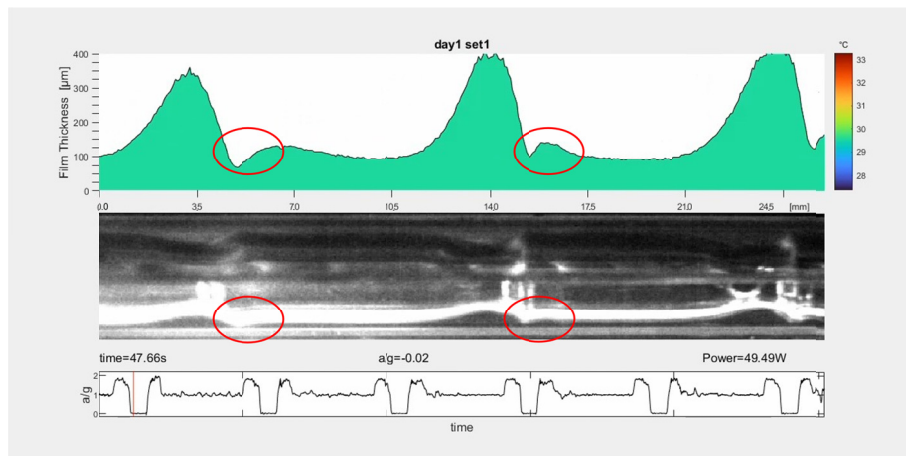


Figure 15. Set-up for measurements of the liquid layer around a bubble in a capillary tube.

The first chart reports the film thickness, measured in the central part of the tube where it can be considered nearly flat; the colour shows the local film temperature averaged along the thickness. The second photo shows the same view in the visible light. The last graph reports the instantaneous gravity level recorded on board of the

zero-G aircraft. The presented frame shows a periodically wavy structure in the annular flow; the noisy ripples at the maximum measured thickness indicates the range limit of the technique, the red markers shows some details captured with high accuracy, that with a visible light technique may seldom appear with only qualitative information.

Future developments

Possible development of the TBS technique may include:

- infrared stereoscopy using two cameras targeting the same film region but with different background surfaces. Like in PIV, the two camera may be positioned on the same side of the target surface, or on opposite sides.
- Use of structured background, to alternate stripes or spot of different temperatures
- Use of reflecting background, also in stripe or spots, to avoid the necessity of a transparent substrate
- Use of high-speed IR LEDs to generate the desired apparent background temperature
- Adapt the TBS principles and algorithm to measure concentrations inside mixtures of liquids and solutions: with more parameters and equations, it could be possible to determine concentration gradients, solute distribution, and mixing efficiency in different systems.
- Adapt the TBS principles and algorithm to measure suspensions in air of particles or droplet, to measure the average liquid temperature across a semi-transparent spray
- Tomographic TBS reconstruction of temperatures profiles across a spray
- Integration with complementary technique (like SLIPI) for full spray characterization

Conclusions

The novel technique named TBS, Twin Background Subtraction, has been developed and successfully tested. It is able to measure simultaneously the temperature and the thickness of an IR semi-transparent layer in the range of thickness where the film is semi-transparent to IR radiation. When tested with water the technique shows promising accuracy in the range of 10-300 μ m, with a precision that could make it complementary to traditional optic techniques more suited for thicker films.

The technique can be exploited with different configurations, and is promising for the study of optically thin films, both solid or liquid, like in multiphase flows involving film evaporation or condensation.

Acknowledgements

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Nomenclature

T_{BG}, T_{BG1}, T_{BG2}	Temperature of BackGround, BackGround1, BackGround2 [$^{\circ}$ C] or [K]
T_F, T_{film}	Film Temperature [$^{\circ}$ C] or [K]
L_F, L_{film}	Film Thickness [m] or [mm] or [μ m]
T_M, T_{meas}	Measured Temperature [$^{\circ}$ C] or [K]
τ	transmissivity [-]
ϵ	emissivity [-]
L	Length, thickness [m] or [mm] or [μ m]
L_0	reference length, reference thickness [m] or [mm] or [μ m]
ξ	attenuation coefficient [m^{-1}] or equivalent

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