Infrared thermography as a heat tracer method for velocity estimation in shallow flows

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Infrarotthermographie als Tracermethode zur Abschätzung der Fließgeschwindigkeiten bei seichtem Oberflächenabfluss

1 Introduction

Shallow flows can be observed in many different situations such as in lakes, estuaries, stratified water bodies, coastal areas, lowland rivers, overland flows or urban basins. The determination of velocity fields in these flows, which are affected by factors such as channel slope and roughness, is relevant for the examination of soil erosion, river morphology or contaminant transport models.

Therefore, the development of accurate and versatile flow measurement techniques is of crucial importance for general hydraulics, hydrology and water resources applications. Over the last 30 years, significant improvements and developments were accomplished. The emergence of powerful new techniques with new capabilities and characteristics, benefiting from the great development of technology in other areas of knowledge, are resulting in higher accuracy and quality of the obtained data. Nowadays, there is a wide range of options available for velocity and discharge measurements that provide good results even under unfavorable conditions (Boiten, 2000). Measurement instruments have to deal with problems such as variability of bed conditions, presence of sediments, accretion and erosion problems, tidal effects, confluence of water masses, or even the presence of vegetation or air-entrainment.

Zusammenfassung

Diese Arbeit zeigt ein Verfahren der Infrarotthermographie um mittlere Fließgeschwindigkeiten anhand der Fließzeit eines Heißwassertracers abzuschätzen. Eine Thermokamera über einer Abflussrinne installiert, ermöglicht die Sichtbarmachung der Oberflächentemperatur des Wassers. Nach Hinzugabe heißen Wassers bildet sich ein helles Muster welches sich hangabwärts bewegt. Dies erlaubt die Abschätzung der Oberflächengeschwindigkeit, die eng mit der Fließgeschwindigkeit korreliert ist. Zur Kontrolle wurden Vergleichsmessungen mittels ADV (acoustic doppler velocimeter) durchgeführt. Die vorgestellte Methode ist als alternative Messmethode bei seichten Abflussprozessen geeignet, wo herkömmliche Verfahren aufgrund der niedrigen Abflusshöhen versagen.

Schlagwörter: Infrarotthermographie, Fließgeschwindigkeit, Oberflächenabfluss, seichter Abfluss, Heißwassertracer.

Summary

This work presents a technique that uses infrared thermography to estimate mean flow velocity, based on the time of travel of a heat tracer (hot water). A thermographic camera, installed above a flume, allows the visualization of the water surface temperature. When hot water is added to the flow, it appears in the footage as a bright mass moving downstream. This allows the quantification of its surface velocity, which corresponds to flow velocity (shallow flows). As a control, results were compared with the measurements obtained by an Acoustic Doppler Velocimeter. This technique is particularly suitable for measurements in shallow flows, where most common flow velocity equipment reveal some limitations due to incompatibilities with low water depths.

Key words: Infrared thermography, Flow velocity, Overland flow, Shallow flow, Heat tracer.

Measurements in shallow water depths are inherently complicated, often challenged by minimum working depths of equipment (e.g. mechanical current meters), vegetation interference, sand deposition, temporal and spatial changes, or even the inevitable interference of boundary conditions (e.g. reflection of waves of Acoustic Doppler Current Profilers – ADCPs). All of these factors contribute for inaccurate measurements and complicate this important task of quantifying the flow and obtaining velocity profiles and fields. Tracer methods contribute to surpass some of these limitations. However, they still raise some environmental concerns, namely the impact caused by the use of dyes.

Infrared technology is a powerful method to monitor surface temperature distribution and has been occasionally used in hydraulic studies. For example in analysis of near surface velocities in oceanic waters (CHEN et al., 2008, 2012 and VERON et al., 2008), or search for groundwater inflows (CAMPBELL et al., 1996; DANIELESCU et al., 2009).

Due to the recent reduction of costs and increased portability of infrared cameras, the application of thermography in water resources, hydrology and soil and water preservation have increased in the last years (PFISTER et al, 2010; DE LIMA, 2014). The use of IR thermography for quantitative flow measurements has not been extensively explored yet and its capabilities have yet to be studied, but some successful examples can already be found in the literature (CHUNG and GRIGOROPOULOS, 2003; LIU et al., 2005; LIANG and CHONG, 2011; SCHUETZ et al., 2012).

2 Methodology

The technique presented in this work uses infrared thermography to estimate flow velocity (surface), based on the time of travel of a heat tracer. The water is heated locally, and acts as a heat tracer, visible through thermography.

The experimental setup (Figure 1) consists in an IR camera hanged 1.5 m above a flume, continuously recording the flow. The flume provided a channel 0.3 m wide and 4.5 m long and the recorded area was 42×55 cm (30 frames per second). Multiple slope and depth conditions were tested.

The resulting footages from the thermographic camera are sequences of greyscale images (temperature maps) where higher temperatures are usually represented by brighter colors and lower temperatures by darker colors. Thus, the heated mass of water is clearly visible as a bright mass moving downstream, allowing the visualization of the surface of the flow. The recorded images are digitally analyzed to quantify

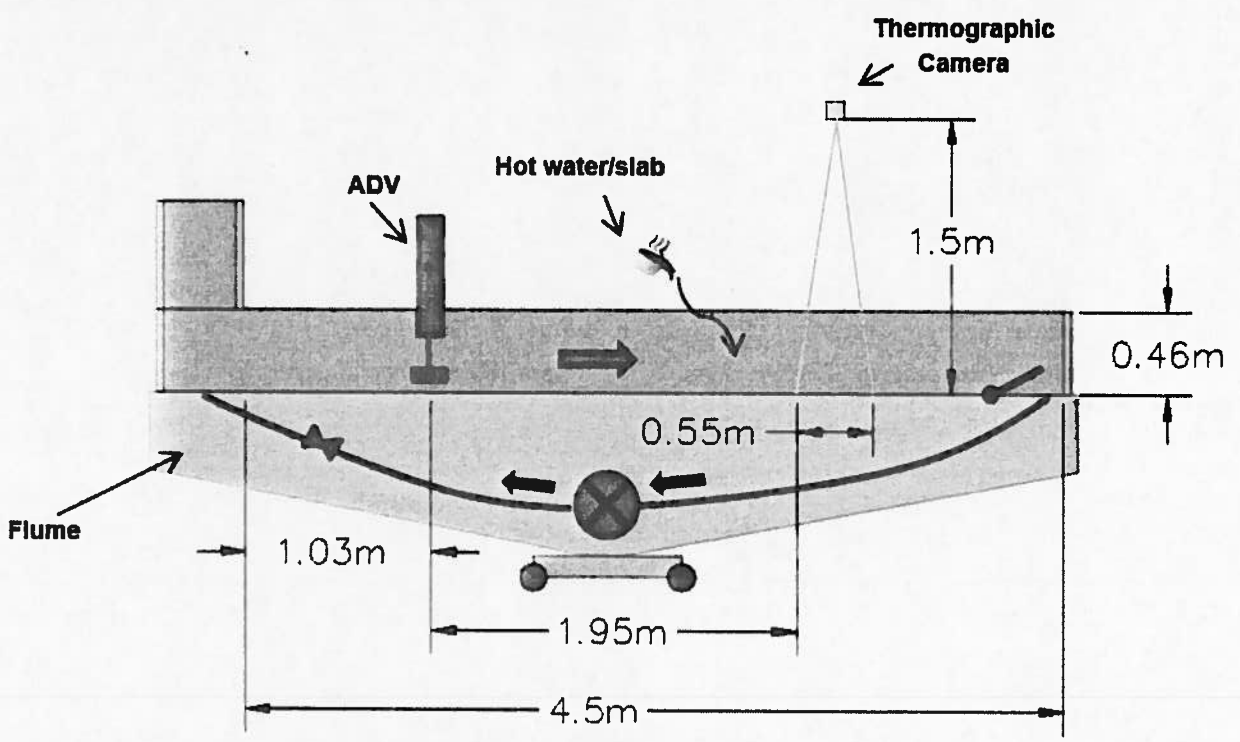

Figure 1: Scheme of the hydraulic circuit and dimensions of the experimental setup (not to scale)
Abbildung 1: Komponenten des hydraulischen Kreislaufs und der experimentellen Modellkonfiguration (nicht maßstabstreu)

the motion (velocity) of the induced heated mass of water, which corresponds to the surface flow velocity (good flow velocity estimation when dealing with shallow flows).

For comparison purposes, a SonTek/YSI 16-MHz Micro-ADV (Acoustic Doppler Velocimeter), a well-established flow velocity measurement technique, was installed. A 2D side-looking probe was used, since it's the most adequate for measurements in shallow water depths.

The heating of the water is a key point of this technique because it directly influences the quality of the visualization. One of the methods used consisted in adding hot water into the flow (water heated by an electric kettle). Ideally, the water should be added homogeneously through the width of the flume, and disturbances to the water surface should be avoided. It was observed that by dropping the water rather than letting it flow slowly out of the recipient, would cause the hot water to sink and consequently complicating its detection by the thermographic camera. Figure 2 illustrates this, and highlights the importance of ensuring that the hot water remains on the surface.

The second water heating method consisted in using a gas torch to heat the edge of a thin metal slab (Figure 3). The edge of the slab is then submerged during 3–4 seconds, allowing its heat to be transferred to the flowing water (slab cools fast when in contact with the water). The slab is placed parallel to the flow, in order to minimize the disturbances caused to the flow.

The resulting thermal images/videos were analyzed frame by frame manually (Figure 4), after the application of visual effects to enhance the visualization of the thermal image analysis (e.g. contrast and brightness adjustments). A start and finish line were defined, separated by a known distance (spatial calibration of the images was done based on the width of the flume). The time when the leading edge of the brighter hot water mass (Figure 5) first reaches both lines was registered, and then used to compute velocity.

a) b)

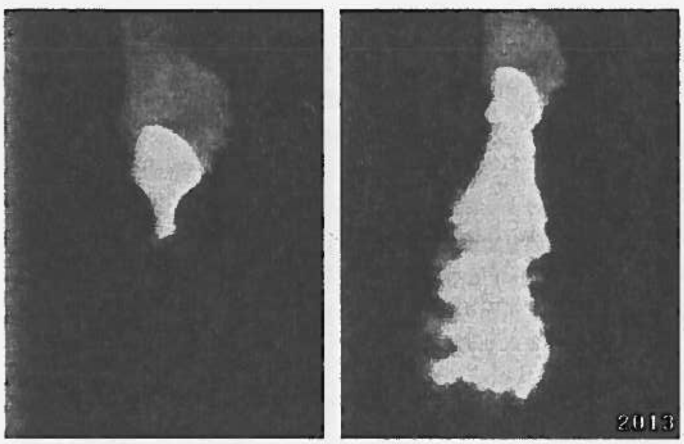

Figure 2: Comparison between two different water addition procedures: a) dropping hot water into the flow (hot water immediately sinks) b) carefully letting the hot water flow out of the container (hot water remains at the surface)

Abbildung 2: Vergleich zweier Wasserzugabeverfahren: a) Zugießen von Heißwasser (Absinken des heißen Wassers) b) gesteuerte Heißwasserzugabe über Behälter (Heißwasser verbleibt an der Oberfläche)

a) b) c) d)

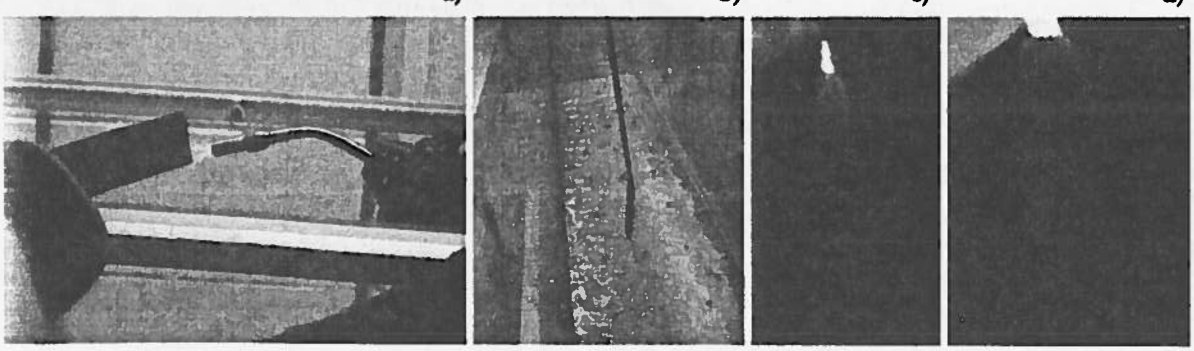

Figure 3: Experiments using a heated metal slab: a) torch heating the slab; b) metal slab placed parallel to the flow; c) IR image of experiments with the metal slab placed parallel to the flow; d) IR image of experiments with the metal slab placed perpendicularly to the flow, causing considerable disturbances (not favorable)

Abbildung 3: Experimente unter Verwendung einer erhitzten Metallplatte: a) Erhitzen der Platte mittels Brenner; b) Metallplatte parallel zur Strömung; c) IR-Bild des Experiments mit paralleler Metallplatte; d) IR-Bild des Experiments mit senkrecht zur Strömung angeordneter Metallplatte (ungünstig, erzeugt Störungen)

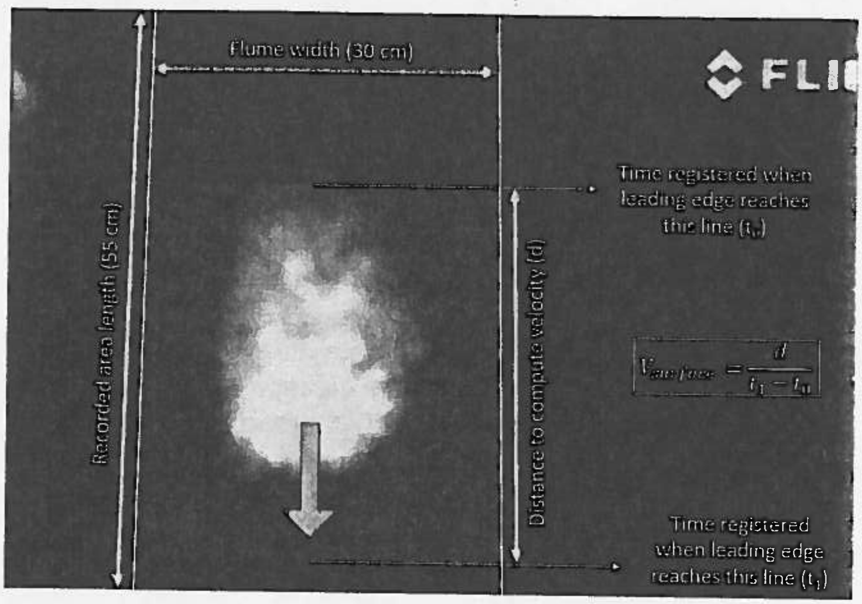

Figure 4: Representation of the procedures for the analysis of the thermal images, with scaling

Abbildung 4: Thermische Bildanalyse mit Skalierung

The automation of these procedures, based on automated detection of changes in pixel color or intensity, would be of interest for future studies and application. Additionally, considering the capabilities of the multiple options for the processing of infrared thermal images currently available (e.g. FLIR software), it would be interesting to perform additional probability-density-function analysis of the images, and to analyze the thermal profiles along the main flow path, or perpendicularly to the main flow.

3 Results and Discussion

In the thermographic images, two distinct fronts of hot water could be identified. This phenomenon resembles with an aureole of less hot water around the intense hotter mass of water, as represented in Figure 5. This aureole was more pronounced when working with lower velocities. Therefore, two distinct velocities could be obtained, one considering the fastest leading front and other considering the most intense front. In this work, the velocity of the leading front was used to infer about surface flow velocity.

Figure 6 shows a comparison between the velocity values obtained using a metal slab to heat the water and by adding hot water to the flow, for three different velocities (both compared with control measurements from the ADV). Each point (thermal) represented in the graph is an average (and corresponding standard deviation) of between 6 and 9 repetitions for each flow condition and procedure. Regarding the ADV, the average of 600 samples is presented, with a signal-to-noise ratio of 40 (flow well seeded).

Results obtained using a slab are systematically lower, with lower variability (standard deviation values fluctuating between 0.52 and 0.66 cm/s). Conversely, the standard de-

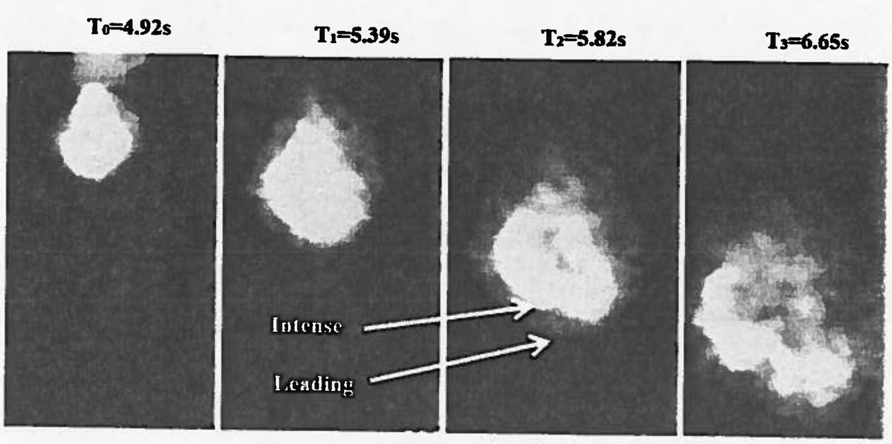

Figure 5: Illustration of the leading and intense hot water front and its movement downstream

Abbildung 5: Abfolge des Transportweges der Heißwasserfront

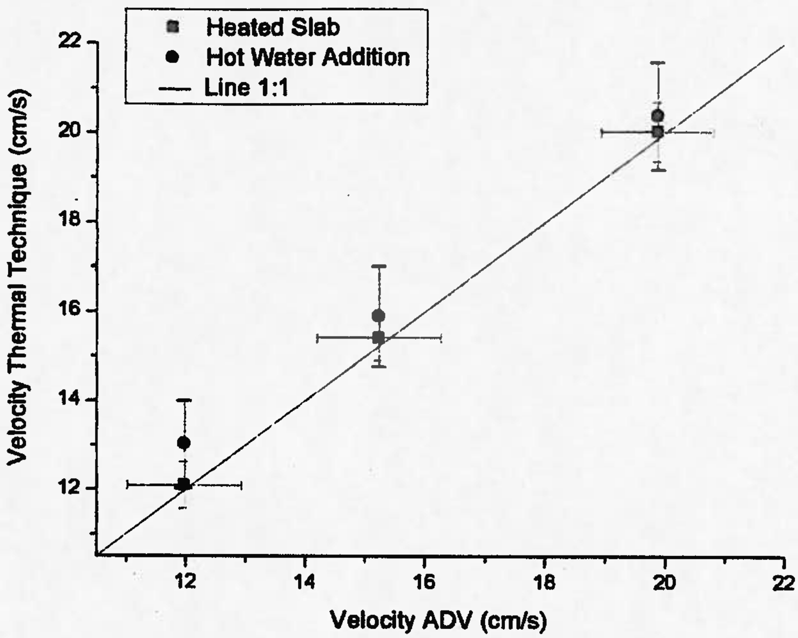

Figure 6: Comparison between the velocities from the thermal technique using a heated metal slab and the velocities obtained using an ADV

Abbildung 6: Vergleich der Fließgeschwindigkeiten der Infrarotthermographie (mit beheizter Metallplatte) und der ADV-Messung

viation values from experiments with the addition of water originated sets with standard deviations over 1 cm/s. In the hot water addition experiments, a slight overestimation of flow velocity was also detected (more noticeable for lower velocities). These results suggest that the use of the slab to heat the water causes less disturbances to the flow, resulting in more accurate results. This is a reasonable conclusion because the movement of inserting the slab in the water is less subject to variations, especially when compared to all the factors that can interfere with the manual addition of hot water.

4 Conclusions

In this work a technique using infrared thermography was outlined and some exploratory experiments were performed for velocity estimation (based on the surface flow velocity). Multiple slope and depth conditions were tested, and the results are in accordance with the velocities obtained using an ADV, although revealing a slight overestimation (higher when dealing with lower velocities). Water surface disturbances negatively affected the estimation of flow velocity with this method.

Different procedures regarding the heating of the water were also tested. The manual addition of water originated higher variability of results (relatively high standard deviation), when compared with the metal slab experiments. The latter consistently presented lower standard deviation values, and provided less overestimated values of velocity.

It is important to highlight that this method is only able to estimate surface velocities. As the velocity profile over the depth of the water is not uniform, the integration of the velocity to obtain the discharge (based on the estimated surface velocity) may cause errors, and thus is not recommended. Therefore, this method is mainly useful for applications in flows with small water depths (shallow flows), where the average flow velocity is similar to the surface velocity.

The main advantage of the technique relies in the fact that the used tracer is the same as the initial fluid in the flow, and thus shares most of its properties (crucial for the success of a tracer). In addition, the formation of conglomerates on the water surface is avoided and no chemicals are added to the flow, resulting in less problems and environmental concerns than with other types of tracers (e.g. dyes). Additionally, the portability of thermographic cameras is also an advantage as it opens good prospects for uses in the field. This method has no constraints regarding the use in the presence of sediments, debris or rocks, which are usually limitations for other flow measurement methods. Considering the recent reduction of the prices of these infrared cameras, this technique and others using thermography, have potential to play a role in the monitoring of shallow flows.

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