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Development of a method using infrared thermography for shallow flow visualization and quantitative estimation of velocity

Dissertação apresentada para a obtenção do grau de Mestre em Engenharia Civil na Especialidade de Hidráulica, Recursos Hídricos e Ambiente

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ABSTRACT

The development of accurate and versatile flow measurement techniques is of crucial importance for hydraulics, hydrology and water resources applications. There is a wide range of options available that provide good results even under unfavorable conditions. However, all methods have their own strengths and limitations. Measurements in shallow water depths are inherently complicated, often colliding with minimum working depths of equipment (e.g. mechanical current meters), or affected by the inevitable interference of boundary conditions (e.g. reflection of waves of ADCPs). Tracer methods contribute to surpass some of these limitations, however they still raise some concerns namely the use of dyes that can cause environmental concerns.

This thesis describes a novel technique for velocity estimation that uses infrared thermography to estimate mean flow velocity, based on time of travel. The experimental setup consists in an IR camera hanged pointing downwards above a flume, continuously recording the flow. Several methods are then used to heat the flow and the hot water acts as a heat tracer that is visible through thermography. The recorded images can then be analyzed to compute velocity. Proof of principle experiments were performed and results are in accordance with the results obtained by the use of an ADV, a well-established velocity measurement technique. Other initial tests were also performed to infer about the most efficient procedures.

This technique also revealed some potential as a flow visualization technique, and leaves space for future studies and research. The use of thermography technology has increased in the last years; it has already been successfully used in hydrology and hydrogeology and can be a useful technique due to its capacities to monitor temperature distribution in shallow flows.

Key Words: Infrared Thermography; Thermal/Heat Tracers; Flow Visualization; Velocity Measurements; Flow Velocity; Shallow Flows.

RESUMO

O desenvolvimento de técnicas precisas e versáteis de medição de velocidade e de caudal é crucial para as diversas áreas da hidráulica, hidrologia e recursos hídricos. Existem inúmeras opções disponíveis que proporcionam bons resultados, mesmo quando confrontadas com condições desfavoráveis. No entanto, todos os métodos apresentam vantagens e limitações para diferentes situações. Em particular no caso de medições em escoamentos em superfície livre de pequenas profundidades, é sempre complicado efectuar medições uma vez que a maior parte dos equipamentos necessitam de profundidades mínimas para funcionarem correctamente (e.g. molinetes mecânicos) ou, por outro lado, a inevitável interferência causada pelas condições de fronteira que podem afectar significativamente os resultados (e.g. reflexão de ondas dos ADCPs). Os métodos baseados em traçadores, apesar de contribuírem para superar algumas dessas limitações, são ainda bastante polémicos como, por exemplo, no caso dos líquidos corados e radioactivos que podem facilmente levantar preocupações ambientais.

Esta tese descreve uma técnica inovadora para estimar a velocidade, utilizando a termografia por infravermelhos para estimar as velocidades médias de escoamento, com base no tempo de percurso de traçadores térmicos. A instalação experimental é composta por uma câmara termográfica instalada em cima de um canal que monitoriza de forma contínua o escoamento. São utilizados diversos métodos para aquecer o fluido escoado, de forma a utilizar a água quente como traçador térmico. As imagens gravadas podem então ser analisadas com o objectivo de estimar a velocidade de escoamento. Foram realizados alguns testes iniciais e foi comprovado que os resultados estão em conformidade com os resultados obtidos através da utilização de um ADV, uma técnica de medição de velocidade reconhecida. Foram também realizados outros testes para analisar quais os procedimentos com melhores resultados.

Esta técnica revelou potencial como técnica de visualização do escoamento, deixando espaço para futuros estudos. O uso da termografia tem vindo a aumentar nos últimos anos e esta tecnologia já foi utilizada com sucesso em diversos estudos na área da hidrologia e hidrogeologia. É uma técnica com potencial em escoamentos pouco profundos devido à sua capacidade de monitorização de temperaturas.

Palavra-Chave: Termografia por Infravermelhos; Traçadores Térmicos; Velocidade de Escoamento; Visualização do Escoamento; Escoamentos de Pequenas Profundidades.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

- **ADCP** –Acoustic Doppler Current Profiler
- **ADV** – Acoustic Doppler Velocimetry
- **BIV** – Bubble Image Velocimetry
- **CCD -** Charge-Coupled Device [Camera]
- **DGV** - Doppler Global Velocimetry
- **DVR** – Digital Video Recorder
- **FPS** – Frames Per Second
- **HWAP** – Hot Water Addition Point
- **IR** – Infrared
- **ITV -** Infrared Thermal Velocimetry
- **LDA –** Laser Doppler Anemometry
- **LDV** – Laser Doppler Velocimetry
- **LIF**- Laser Induced Fluorescence
- **PCA** – Planar Concentration Analysis
- **PDV** – Planar Doppler Velocimetry
- **PIV** – Particle Image Velocimetry
- **PLIF -** Planar Laser-Induced fluorescence
- **PTV** –Particle Tracking Velocimetry

1. INTRODUCTION AND OBJECTIVES

1.1. Framework and Motivation

Accurate flow measurements devices and techniques are crucial for the success of most activities related to hydraulics and water resources management. Over the last 30 years, significant improvements and developments were accomplished, not only resulting in higher accuracy and quality of the obtained data, but also with the emergence of powerful new techniques with new capabilities and characteristics, benefiting from the great development of technology in other areas of knowledge.

The knowledge of velocity profiles are of engineering interest, thus worth of research focus. Velocity, and consequently discharge (e.g. velocity-area method), is inherently difficult to measure. Not only the velocity varies in time, varies in depth and it also varies along the width. In addition, 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. All of these factors contribute for inaccurate measurements and complicate this important task of quantifying the flow and obtaining these velocity profiles and fields.

There are however plenty of options for velocity measurement. Most of the principles used for pressurized flow measurements can also be applied for open channel flows, naturally with the proper adaptions to face the added complexity originated, for example, by stage or cross-sectional area variations. However, although these methods are accurate for measurements under certain conditions, they all have significant limitations. As an example, most instruments can’t operate at shallow depths.

Shallow flows, as part of the hydrological cycle, often appear in many natural and urbanized catchments. Also, with the increasing demands on water resources, shallow flows have gained additional importance. For example, shallow flows are the basis for the design of rainwater harvesting from parking lots or rooftops. The knowledge of shallow flow behavior is of engineering interest, due to its implications in water quality, water reserves characterization and importance for low-slope hydrology. However, the characterization and quantification of this kind of flows is not easy to achieve, due to its low depths and inevitable conflict with minimum working depth of measuring instruments that result in considerable uncertainty.

Identically, research works have also been focusing on flow visualization techniques, thus new and powerful techniques are emerging, and the existing ones are being improved and used for different applications. These techniques allow obtaining both qualitative and quantitative information that can be useful to study various processes and situations. Particle Image Velocimetry (PIV) is an example of these methods, and allows the quantification of velocity fields.

Within these flow visualization techniques, thermography appears as a relatively new technique concerning its application in water resources, hydraulics and hydrology. It has however considerable potential for remote detection of velocity patterns (e.g. oceans) or for uses in groundwater or karst hydrology, relying in the detection of natural or artificially induced temperature gradients. The increase in the use of this technology in the last few years is explained by the decrease in the price of thermographic cameras, and by its increasing portability that eases its use, especially in the field.

1.2. Principle

The present thesis consists in the description, proof of principle and some initial experiments of an emerging technique for estimation of flow mean velocity. The technique uses inexpensive infrared thermography for visualization and quantification of the motion of an induced heated mass of hot water acting as a thermal tracer.

The resulting footages from the thermographic camera are sequences of greyscale images (depending on the camera and software used), which are 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. By relying on time of travel considerations, the flow velocity can be computed through Equation (1.1), by relating spatial and temporal information from the recorded images, as represented in Figure 1.1.

$$V = \frac{X}{t_1 - t_0} \quad (1.1)$$

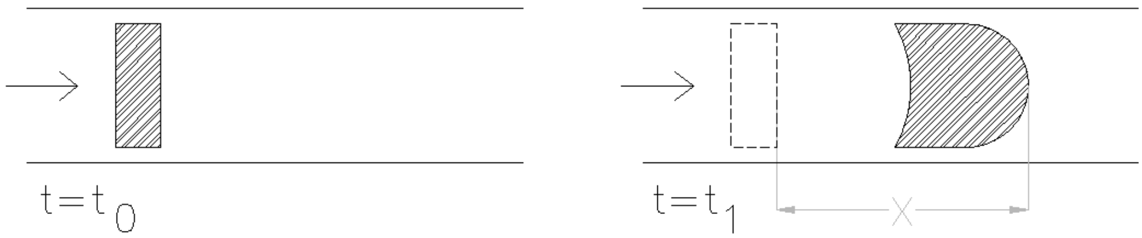

Figure 1.1 - Idealized moving hot water mass.

Ideally, the water should be locally heated along the full stream width, while causing minimum disturbance to the flow as possible, and as homogeneously as possible. Besides velocity estimation, this technique can also be useful as a flow visualization method. It is possible to obtain the horizontal velocity profile and turbulent structures can also be identified.

The similarities of this method with the tracer velocity method are evident. Thus, it can be viewed as a variation of these methods, usually used with dyes or salt solutions, but using a heat/thermal tracer instead. Hot water is likely to perform well as a tracer. As hot water is still water, most of the characteristics remain approximately the same, thus this tracer similarity with the stream fluid makes it close to an ideal tracer. However, some of these properties are known to vary with temperature, such as density or viscosity. As can be easily computed from a temperature-density relation table, water density at 80ºC (ρ = 0.9718 g cm^{-3}) is only around 2.7% lower than the density at ambient temperature (for 20ºC, ρ = 0.9982 g cm^{-3}). This difference is most likely not significant for this technique purposes and the hot water will follow the motion of the flow properly. However, hot water will have tendency to remain by the top layers, what can actually be an advantage, because it will enhance surface visualization through the thermographic camera, as it will be described later on this thesis. Nevertheless, Schuetz et al. (2012) in a similar technique applied to wetlands, added a salt solution to approximate the densities and reduce this difference. In addition, the absence of tracer particle agglomeration is also an advantage, when compared to other tracers (e.g. dyes, salts).

The purpose of this thesis is then to present this two dimensional (planar) technique that can be useful to surpass some of the most common limitations of conventional velocity measurement methods, namely when dealing with shallow water depths, where most instrument can´t operate because of their limited operating depths. Other important strengths are the simplicity of the setup, which requires relatively inexpensive technology and little calibration, and the fact that no residue is left on the water (heating might have influence, but only small volumes are involved).

1.3. Objectives

The main objective of the present thesis is to contribute to the development and design of an innovative technique for mean velocity estimation using inexpensive thermography technology and to perform exploratory experiments to test the system (proof of principle).

More specific goals include:

- Overview of the most common measurement and visualization techniques and identification of their main limitations.
- Contextualization of the technique within these velocity measurement techniques.
- Study the feasibility of the technique, by comparison with a well-established velocity measurement technique.
- Initial laboratory experiments to test the technique for different conditions;

- Optimization of procedures in order to improve results, namely:
  - Comparison of results using different heating methods;
  - Image interpretation options.
- Definition of a range of applicability.
- Identification of future work prospects.

1.4. Thesis Structure

The present thesis is subdivided in the following chapters:

- Chapter 1 – Introduction to the scope of the thesis, principle used in the technique, objectives and structure of the thesis.
- Chapter 2 – State of the art about flow measurement, overview of the different types of available techniques. Identification of their most significant limitations.
- Chapter 3 – Overview of techniques on water flow visualization. Introduction to thermography technology and some of its most relevant applications for hydraulics and water resources.
- Chapter 4 – Presentation of the experimental installation, equipment and materials used in this work. Description of the methodology and outline of procedures.
- Chapter 5 – Presentation and discussion of the results.
- Chapter 6 – Conclusions, outcomes and future work.

2. WATER FLOW MEASUREMENTS

2.1. Initial Considerations

The measurement of flow (e.g. discharge, velocity, water depth) has always been crucial for many different domains. With the management of water resources being a hot topic of the present times, flow measurement must be seen as fundamental for the planning activity. Flow measurement provides information about the availability of water resources and its variability in time and space, allowing a more integrated approach that can be used to support water management. Knowing the amount of water available is the most important starting point for determining the best uses for it, reducing the losses and negative environmental impacts. The planning activity should start with a deep characterization of the study zone in order to identify the problems (diagnosis) and analyze the available alternatives for solving the problems and defining the impacts of each of these alternatives. All of these phases depend on the quality of the available data, such as flow discharge, and are valuable inputs for methods of decision making support.

The multiple demands for water use also require flow measurement to be accurate. Irrigation systems are the most recurring example in literature for justifying its importance. Problems like ensuring a proper distribution of the available water to the multiple users or crops damaged by overwatering are often referred. Also in the water distribution systems, flow measurement is fundamental, with proper water losses assessment and water billing being the key point. Many other activities rely on these measurements for its operation such as hydroelectric power generation or industry. It’s also important to emphasize the implications it can have in the cost.

Also in flood control, flow measurements are the basis for the prediction of water levels and storm water runoff monitoring, allowing the implementation of measures to minimize the impacts of floods.

Design of hydraulic structures such as channels, water storage reservoirs, dams, flood control structures, can’t be effectively accomplished without quantifying the discharge that the structure needs to be able to handle.

Finally, with the recent environmental concerns, quality control of water resources has become a priority, with considerable pollution control efforts being made. For example, industrial wastewaters are now required to comply with regulations limits, and the polluter-payer principle is being applied. All these environmental measures depend on measuring the discharge and analyzing its chemical properties, in order to quantify their pollution indicators.

Besides the importance of knowing discharge, the knowledge of velocity is also vital for many studies. For example, soil erosion is a function of flow velocity, meaning that it must be known to allow the calibration of models for its quantification. Similarly, velocity is also fundamental in pollutant transport and dispersion modeling.

In addition, flow discharge and velocity undoubtedly influence aquatic organism energy expenditure, food delivery, waste removal, predator avoidance, and disturbance. Thus, their measurement is important for its analysis and environmental studies (Hart, 1999).

The research process, in order to obtain valid results, needs accurate data to be analyzed. Flow discharge and velocity fields are examples of crucial data for researching water related issues. For example, (Biron et al., 2004) emphasize the need for accurate flow field data (discharge, velocity, boundary conditions) for parameterization, calibration, and validation of their developed one-, two-, and three-dimensional river models.

All of these aspects contributed to the development of flow measurement techniques along the years. In the last few years, new techniques are becoming more popular while others that were massively used in the past are getting obsoletes due to the development of new and more effective techniques.

2.2. Shallow Flows

Shallow flows are flows where the water depth is significantly smaller than the width (width to depth ratio is significantly bigger than 1). This type of flow is known for being turbulent (Uijttewaal et al., 2001).

Shallow flows are quite common and they can be observed in many different situations such as in lakes, estuaries, stratified water bodies, coastal areas, lowland rivers, overland flows or urban areas (Jirka & Uijttewaal, 2004). The determination of velocity fields in shallow flows is crucial for the success of soil erosion, river morphology or contaminant transport models, since it’s one of their most important input parameters. Velocity in shallow flows is affected by several factors, including channel slope or roughness.

Computers already have capacity to solve 3D models for this kind of flow (Vreugdenhil, 1994). For example, commercial fluid dynamics simulation software (e.g. FLOW-3D, OpenFoam, Fluent) can be used to model three-dimensional flows with free surfaces and complex channel geometry (Hirt & Richardson, 1999). However, attending to the fact that the processes in the horizontal plane are clearly dominant, 3D interactions are often neglected and shallow flows are analyzed through simplified 2D models that still provide good approximations.

Shallow flows can be difficult to measure using conventional methods, mostly due to minimum working depths of measuring devices, vegetation interference, sand deposition or temporal and spatial changes. In the laboratory, volumetric methods (see section 2.4.1) are widely used, but they are unsuitable for field measurements, where tracer methods (section 2.5.9) are one of the best options for its measurement.

2.3. Techniques for Open Channel Flows

There are plenty of options for discharge and velocity measurements in open channel flows. Different authors have been grouping them differently (Holman, 2001). In the present thesis, discharge measurements were separated from velocity measurements, although they are related. Other grouping options could consider, for example, single or continuous measurements, accuracy or applicability (field or laboratory).

The selection between the multiple existing measurement instruments and techniques is made accounting for many variables related to the equipment itself (e.g. cost, installation process, portability, availability of power source, dimensions, software) or for the goal of the measurement (e.g. single or continuous measurement required, precision/accuracy needed, hydraulic conditions). For example, if the objective is to calibrate one specific method, we might not need an expensive accurate method with continuous record of flow. Also, there are many constraints and limitations (e.g. depth, accessibility) that will lead to choosing a method over the others.

To summarize, the determination of discharge and/or velocity is not an easy task. For each case, the most suitable method should be used, and the user should be aware of its uncertainties and limitations. The following sub-sections give an overview of the available techniques, referring its basic principle as well as their main advantages and limitations, especially when applied to shallow flows.

2.4. Discharge Measurements

There are several ways to measure discharge. Some of the techniques give discharge directly (e.g. volumetric and gravimetric). However, discharge is often obtained indirectly, by measuring different components separately (e.g. velocity, stage, and channel geometry). In control section methods (e.g. weirs, flumes), discharge can be computed from the upstream stage, while in the Area-Velocity method (section 2.4.4) velocity measurements are used for the same purpose. In both cases, the use of secondary instruments is required, for the knowledge of water levels and cross sectional geometry, respectively.

2.4.1. Gravimetric and Volumetric Methods

The principle of both methods is simple: it consists in collecting the entire flow in a reservoir and compute discharge by dividing the quantity of water collected by the corresponding period of time.

In the gravimetric method, this can be done by weighting the amount of water collected during a given time period. Similarly, the volumetric method follows the same principle, although measurements involve measuring the volume of collected fluid instead. Due to the nature of the measurements, this option is less accurate than the gravimetric one, despite not requiring a weighing scale (a reservoir with a known volume is enough), what can be an advantage in field measurements.

These method have some evident limitations since they can´t identify changes in the flow rate and it can't be used for continuous measurements (the computed discharge is an average flow rate during a given time period). Another significant limitation is that it can only be used for low discharge values and for narrow stream concentrated flows. It is, however, a useful technique for small and simple field and laboratory measurements (Grant & Dawson, 1995). With accuracy values that can reach ±0.04%, gravimetric methods are probably the most reliable option for discharge measurements, and are often used as reference values in laboratories. (LEHid/LNEC, 2008)

2.4.2. Natural and Artificial Control Sections and Hydraulic Structures

The goal of a control section is to maintain a flow with well-defined characteristics (critical flow). An ideal control section varies neither in space nor in time. These control sections can be natural or artificial, as long as they are stable in order for the rating curves (discharge versus stage graph) to remain valid. When weirs or flumes are built, they induce changes in water level in the nearby region. Under these critical conditions, discharge can be computed only from the upstream stage (downstream head has no influence), since there is a unique water level for each value of discharge. For artificial control sections, the relation between stage and discharge is well known, so tabulated ratings can be used (Grant & Dawson, 1995). Flow measurement through this method requires auxiliary methods for stage determination, often referred as secondary methods.

Weirs are hydraulic structures (Figure 2.1a) where an obstruction to the flow is applied in order to obligate the water to flow though the opening (notch). Weirs are often classified by the shape of the notch that can be rectangular, V shaped (V-notch) or trapezoidal (Cipolletti).

Flumes can be described as an artificially shaped channel flow section (Figure 2.1b), where the area and slope are modified, forcing the flow to acquire critical conditions, resulting in changes in velocity and stage. This is usually obtained by a contraction of the section (vertical and horizontal), restricting the flow, followed by expansion to the normal channel width. The most common flumes are Parshall flumes, ramp flumes and trapezoidal flumes (Bos, 1985).

Submerged orifices can also be used for flow measurement in open channels. An orifice is a well-defined, sharp-edged opening in a wall, through which flow occurs.

Discharge can be computed from the variation between upstream and downstream head and from the characteristics of the orifice. Submerged orifices result in less head loss when compared to weirs. However, they have more problems with the deposit of sediments and other objects that may cause obstruction of the orifice. They're usually installed when the conditions for building a weir or a flume are not adequate. (USBR & USDA, 2001)

The main limitation of these control section methods is that they require building a structure which, sometimes, it's neither possible nor desirable. Besides, unstable bed conditions, ice and vegetation obstruction may reduce accuracy. Thus, regular maintenance is crucial to ensure data quality. It is also an intrusive method which changes the conditions of the flow by placing an obstruction to the flow.

a) **b)**

Figure 2.1 - Example of hydraulic structures for flow measurements: a) sharp crested weir (Geocashing, 2013); b) flume (Clearfield County, 2013).

2.4.3. Empirical Formulas (Slope-Area Method - Control Channel)

Flow can also be estimated using empirical formulas and coefficients. For example, the Gauckler–Manning–Strickler formula can be used to compute discharge or velocity, based on some parameters such as the cross sectional area of flow, hydraulic radius, average slope, and the coefficient of roughness. However, this method implies the use of auxiliary methods to determine the referred parameters (Boiten, 2000).

Manning roughness coefficients have been tabulated for many different conditions and materials. Its determination has been object of many research studies. Nevertheless, this coefficient actually involves parameters such as surface friction or wave resistance that originate uncertainties. Therefore, its determination is difficult for densely vegetated zones, shallow flows, or in alluvial channels with continuously changing bed forms, whose complexity of processes complicate this task. Ding et al. (2004) presented a numerical method based on optimal theories for identifying Manning roughness coefficients in shallow water flows, that emphasizes the difficulties that can be found when applying this method, under these conditions. Furthermore, the application of these formulas can be seen as a control channel method, which implies the existence of an uniform flow. Therefore, in order to successfully apply the Manning formula, some hydraulic and geometric conditions must be fulfilled.

Similarly, other formulas can be used, such as Chézy's formula that considers mean velocity as a function of the hydraulic radius, the bottom slope and the Chézy coefficient (e.g Dalrymple & Benson, 1984; Hershy, 1995).

2.4.4. Area-Velocity Method

The Area-Velocity method uses the continuity equation to compute discharge from the geometry of the cross section and from the mean velocity in this same section. In order to compute these quantities, the cross section is divided into several subsections (Ardiclioglu et al., 2010). The geometry is obtained by performing stage measurements in each one of them (depth at the middle of the subsection). Mean velocity is obtained from single point velocity measurements at different verticals and depths along the width of the stream. However, the adoption of a mean velocity to describe the velocity in the cross section is a considerable simplification. The distribution of the velocity of the cross section is non-uniform and exhibits considerable variation both through the depth and width, as represented in Figure 2.2. Vertical profiles have a parabolic distribution of velocity, with the point of maximum velocity occurring around 10% of total depth below the surface. Horizontally, the maximum velocity occurs in the center of the channel, decreasing as it approaches the edges.

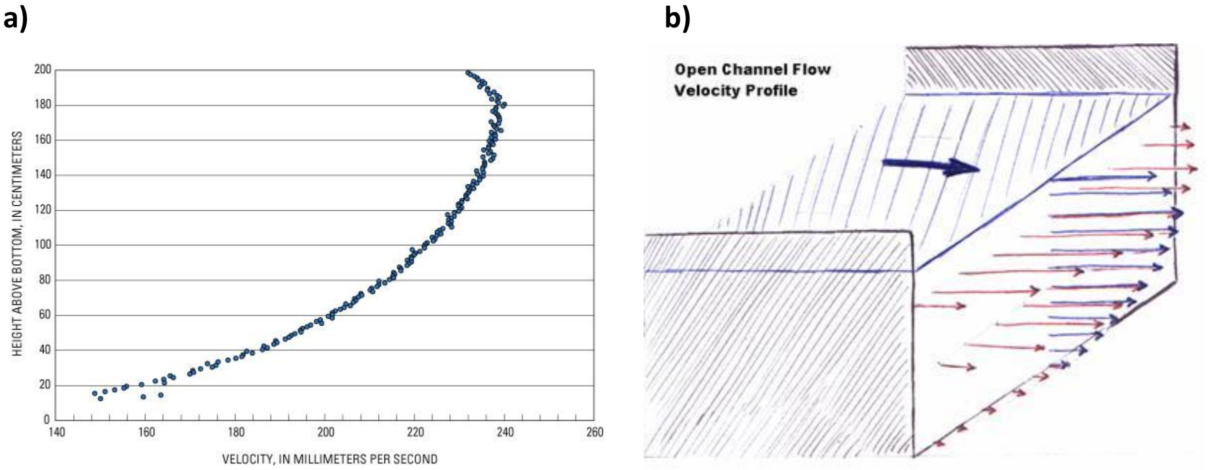

Figure 2.2 - Velocity variations in the cross section (Rantz, 1982): a) typical vertical velocity profile obtained by an ADCP; b) schematic of the velocity variation in the cross section.

In order to properly describe velocity fields, different readings at different depths and at different verticals along the width of the stream are necessary. Ideally, mean velocity would be computed from the integration of velocity profiles. As a simplification, there are several methods to establish the relationship between these readings and the mean velocity at each subsection, such as the vertical velocity curve method, the two point method, or the six tenths depth method (Buchanan & Somers, 1969). These methods may require a variable number of readings, feature different accuracy, and be more suitable for distinct situations (depth, vertical variations in water speed, equipment used). These methods are crucial to properly estimate the mean velocity of the non-uniform vertical velocity field of open channel flow.

The accuracy of the method increases with the number of subsections studied and with the number of measurements in each vertical. It's also important to ensure that the main flow direction is perpendicular to the cross section, thus the selection of the measuring site and section is important for the success of the method.

Measurements may require various pieces of equipment (e.g. cablecars for transportation of the operators, unmanned cableways, bridgeboards, cranes for measurements from bridges) (Hershy, 1995). The need for extra equipment increases the cost of the measurements and complicates the execution.

2.5. Velocity Measurements

Velocity measurement techniques can measure velocity locally (single direction, or 3D), or can measure the mean velocity directly. There are also methods that can swipe the full depth (and width) and obtain the velocity profile (e.g. ADCP or current meters together with a boat). Finally, some methods allow to measure the velocity continuously, while others can't consider the time variable, thus disregarding variations of velocity with time.

2.5.1. Force Displacement

Force displacement methods are based in the principle that the strength of the water against a mass is proportional to flow velocity.

An example of these methods is a deflection meter, where a vane (vertical or horizontal axis) is hanged into the flow and its deflection is measured. Vanes can also be used to directly obtain the discharge (e.g. Larsen, 1992, USBR & USDA, 2001). For this purpose, vanes have to be calibrated and shaped accordingly to the geometry of the channel. Although vanes are expensive, they can be used in multiple sites by installing them in permanent pivots that are usually built to support the removable vanes. Similarly to traditional current meters, vane deflection meters should not be used if the flow contains considerable amounts of solids and sediments because it might damage the equipment.

Pendulum type meters are another good example of force displacement methods (Boiten, 2000). In this case, a submerged mass is hanged by a wire (similar to a pendulum) and flow velocity can be estimated by measuring the angle of displacement of the wire.

Depending on flow velocities, masses of different shapes and materials are available. Coefficients may be necessary for corrections for the bending of the wire. This technique is useful for measurements in shallow rivers or channels.

The effect of wind in the exposed part of both the vane and the wire from the pendulum can originate significant errors, which can, however, be minimized by installing a windbreak system.

2.5.2. Velocity Head Rod

This simple and inexpensive technique uses the proportionality between flow velocity and the upstream height increase (jump) caused by the insertion of a graduated rod in the water (Boiten, 2000). First, with the sharper edge pointed upstream, the stream depth is measured. The rod is then placed sideways to the flow, originating an obstacle that causes disturbance upstream of the rod, namely a jump. By measuring the depth for these new conditions, the height of the induced jump can be computed and used in tables or abacuses that provide the corresponding velocity (Carufel, 1980).

This technique is useful for casual measurements in small streams and works well in the presence of debris or vegetation. It has some limitations, namely the difficulty of detecting depth variation for slow velocities or in holding the rod against the flow (Fonstad et al., 2005).

2.5.3. Anemometry

Hot Wire Anemometers

This method's basic principle consists in relating the fluid velocity to the heat lost when placing a heated wire in contact with the moving flow. The transfer of heat to the surrounding fluid can be measured by monitoring the energy needed to maintain a constant temperature in the wire. Different kind of probes can be used, and they are chosen taking into consideration many factors, such as the type of flow to be measured, medium (e.g. water, air; widely used for measuring wind velocities) or the expected velocity range. Some examples of probes are wires, fiber, films or arrays (Jørgensen, 2002). This technique requires computational analysis and calibration. Because the sensors are fragile, this technique can't be used under aggressive conditions (e.g. presence of debris or sediments).

This technique only provides a measure of the turbulence within the flow. Thus, its aim is different of the other techniques here presented and it is only here described to emphasize this difference.

Laser Doppler Velocimetry (LDV)

Laser Doppler Velocimetry (LDV), also known as Laser Doppler Anemometry (LDA) is a well-established optical method for single point velocity measurements (Drain, 1980). Similarly to other methods, the flow has to be seeded with particles prior to the experiments. The method involves the use of two continuous laser beams converging at one point (Albrecht et al., 2003). When tracer particles pass through that point, they reflect the incident light back to the optical system. By collecting this scattered reflected light (backscatter) and analyzing its Doppler shift in wavelength it's possible to obtain the local 3 different components of velocity.

2.5.4. Mechanical Current Meters

Current meters are devices to locally measure the velocity of flow (Figure 2.3). The water movement induces the rotation of a small rotor that can be installed on a vertical or horizontal axis. The velocity of the water can be computed from its proportionality with the angular velocity of the rotor (Boiten, 2000).

The use of current meters has some limitations or drawbacks (Hershy, 1995). Depending on the depth and width of the channel we intend to measure, the application of this method may take a long time (pulsating flow requires each single reading to last for at least 40seconds in order to minimize errors. Taking a long time to obtain the readings can be a problem, especially if rapid changes in stage are expected, jeopardizing the results. Current meters have also minimum working water depths that can be an important limitation if shallow flows are to be measured. For this type of flow, pygmy meters are the best option, with minimum working depths of around 9.14 cm. Besides, current meters don't work for flows that are too slow. For example, a pygmy meter needs velocities over 1.83 cm/s in order to be able to detect it. The presence of debris and sediments also restricts the use of current meters, since it may damage them.

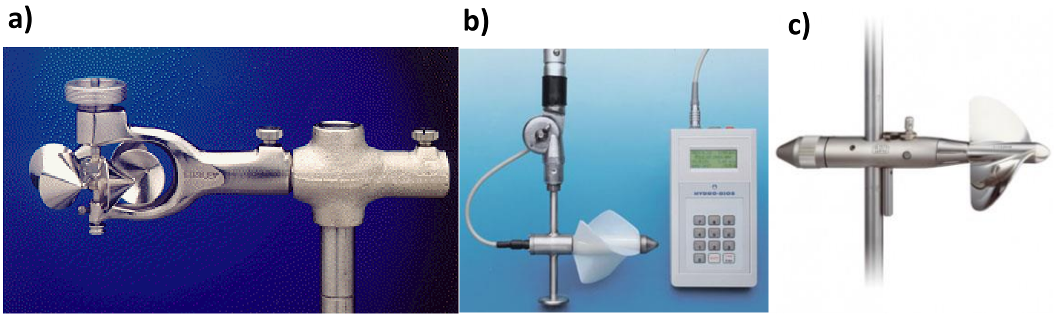

Figure 2.3 - Example of current meters: a) pygmy-price (Gurley Precision Instruments); b) propeller type (Hydro-Bios; c) propeller type (Scottech).

Another relevant outlook is that current meters must be kept in good conditions, which require effective maintenance. Without it, the current meter rating (table relating velocity of the rotor with flow velocity) will most likely provide incorrect values for local velocity.

Many other aspects are susceptible of reducing the instrument accuracy such as the interference caused by the operator legs while using the current meter or even the influence of vertical walls proximity. In order to obtain the best possible results, the choice of a good measuring site is fundamental. It should comply with some criteria, which include the flow being as rectilinear and regular as possible (flow predominately in a single plane), the use of a stable cross section. Otherwise, velocity vectors with different directions (e.g. downwards or sideways) may cause the meters to spin faster and compromise results (Rantz, 1982).

To sum up, the application of this method should be done carefully, because otherwise, its results may be erroneous.

2.5.5. Electromagnetic

According to electromagnetic induction principle (Faraday), when water flows through a magnetic field it generates a voltage. The magnitude of this induced voltage can be used to compute the average velocity of the flow.

Based in this principle, electromagnetic flow sensors (e.g. Boiten, 2000; Aqua-Data, 2013) comprise a probe equipped with electrodes that sense the voltage induced by the moving water (Figure 2.4b). These probes have no moving parts and don’t require calibration (after manufacturer). These devices feature high sensitivity and accuracy, making it a very versatile instrument that is suitable for measurements in several unfavorable conditions including shallow or low velocity flows. Although these meters require a minimum conductivity of the medium (5 μS), this is usually not a problem for uses with water (clean fresh water conductivity around 50 μS). It is also unaffected by debris or suspended solids in the flow. Its portability and ease to use are also advantages of this technique.

Newman (1982) developed a large scale application of this electromagnetic method for measurements in a rivers (Figure 2.4a). In order to create the magnetic field, an electromagnetic coil is buried under the river bed, and the voltage is picked up by electrodes in the stream banks. Depending on the bed properties (e.g. conductivity), the induced potential may be significantly attenuated. To solve this problem, a membrane can be used to isolate the flow from the river bed, however implying an increase of the cost of the technique (material and installation). The application range of this method is one of its most important advantages, since it allows surpassing most common flow measurement limitations: there are no problems with vegetation, debris content, temperature stratification or variations in stage. Besides, despite the need to build a permanent installation, the resulting gauging station does not change the flow conditions (stage) nor becomes a barrier for fish. This method is mainly used in channels with widths up to 25meters. Despite the usefulness of this technique, electromagnetic river gauges have lost popularity and river gauges are no longer being manufactured, due to a fall in demand (Child, 2012).

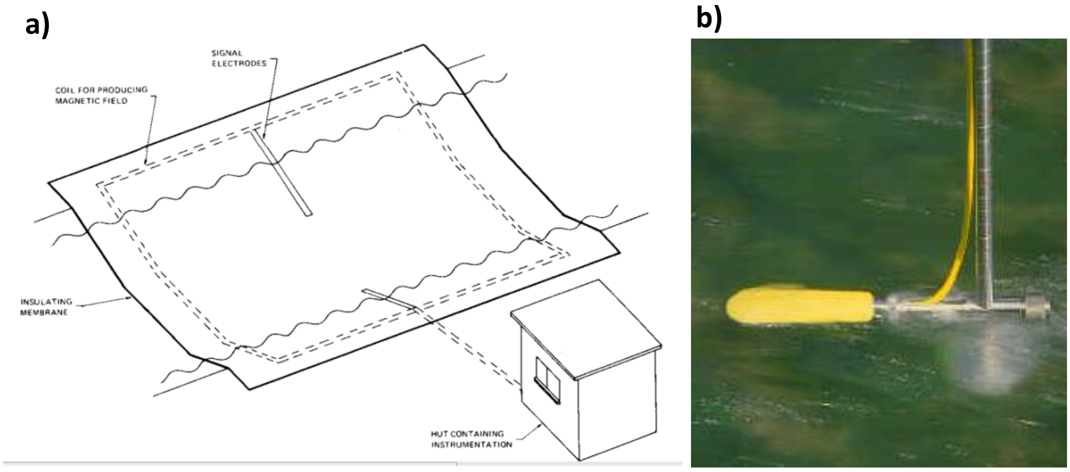

Figure 2.4 - Electromagnetic measurements: a) large scale electromagnetic river gauge (Newman, 1982); b) current meter (Quantum Dynamics).

2.5.6. Acoustic Devices

Ultrasonic (Transit Time Acoustic Meter)

This method uses ultrasonic signals to measure flow velocity. Transducers are placed in the water stream and transmit timed pulses to the opposite transducer (or reflector) (e.g. Newman 1982; Boiten, 2000). Since the transducers are placed with an angle relatively to the direction of the flow, the transit time of the signals between transducers varies due to the influence of the moving water mass. These variations in transit times can then be processed to compute flow velocity.

This technique offers better results for channel widths larger than 25 meters. It may, however, evidence problems with signal paths closer to the surface or to the stream bed due to interference caused by signals reflected by boundaries, not being well suited for shallow flows. Temperature stratification may cause the beams to bend and not to reach the corresponding transducer. This can be explained by the dependence of speed of sound on water temperature. Same beam bending can occur in estuarine waters or confluences where water mixing causes signal reflections. Besides, in these crossed flows, the direction of flow might not be easy to determine. This has implications in the final result, since the angle between the signal path and the flow is used for computations. For these reasons, the site selection gains crucial importance for the success of this method.

Acoustic Doppler Current Profiler (ADCP)

The Acoustic Doppler Current Profiler (ADCP) technology uses the Doppler Effect to compute the velocity profile of a stream (Grant & Dawson, 1995). The Doppler Effect principle states that, as a result of relative motion between the source and the observer, there is a change in the apparent frequency of the wave. The ADCP device comprises four transducers (Figure 2.5a) that transmit high frequency sound waves (acoustic pings) that are reflected by moving particles or air bubbles from the flow. Due to the Doppler Effect, these reflected waves are collected again by the same ADCP with a different frequency values, allowing to compute the relative velocity between the moving particles (assumed to be the same as the flow velocity) and the ADCP equipment (fixed or also in motion). Three of these transducers are used to compute the velocity in 3 dimensions, while the 4^{th} transducer is mainly used for error corrections (Rantz, 1982).

ADCP is a current profiler, meaning that velocity is not measured locally, but a profile is obtained instead. This data can be used to compute discharge by integrating the velocity profiles for the full cross section (e.g. area-velocity method). For this purpose, ADCPs are usually installed in a moving boat in order to swipe the entire cross section of the stream (Figure 2.5b). The emitted sound signals can be used simultaneously to measure the stage by time of travel principle. In addition, ADCP devices are also equipped with a pendulum and a gyroscope that allows them to measure their own speed, in relation to a fixed point in the stream bed (explains the reduced accuracy of this method when movable beds occur). However, there are regions of the cross section that can´t be measured. Close to the surface, there is a region called blanking distance (length for submerging the ADCP device plus the length transducers need to detect the signals). Near the bottom of the cross section and in regions close to the shore or vertical walls there is also lot of interference with rebounding waves (side lobe interference). Because only part of the cross section is measured and to avoid underestimation of discharge, the missing velocities have to be estimated based on an idealized velocity distribution, which introduces uncertainty (Rantz, 1982).

In order to detect the reflected sound waves, there must be particles in the water. However, air bubbles originated by the turbulence of the water flow are usually enough for this purpose. Because of interference caused by reflections from the boundaries (e.g. surface and bed), this technique only allows working depths over 0.5m (Forray, 1998).

This method can provide accurate and quick results, which are useful when measuring rapidly changing flows (e.g. tides), surpassing the traditional time consuming current meters measurements.

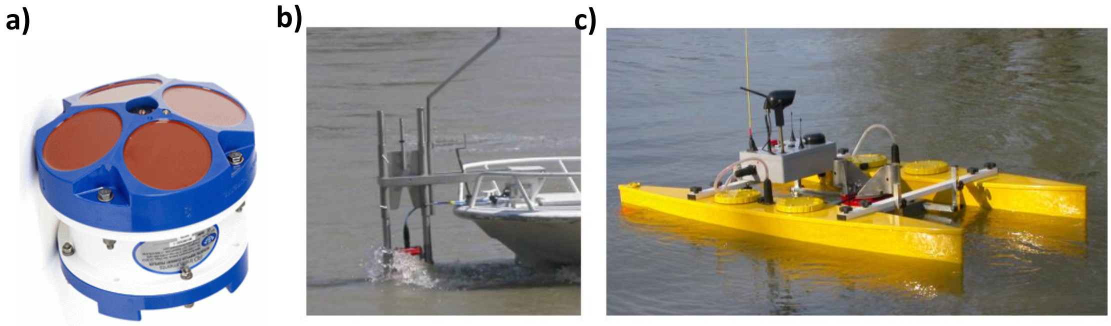

Figure 2.5 - a) ADCP (Teledyne RD Instruments); b) ADCP attached to a boat (Coz, 2008); c) ADCP remotely controlled boat (Coz, 2008).

The ADCP method has also been used horizontally, by fixing several side-looking ADCP on the sides of the stream (Child, 2012). This variation is called H-ADCP and has provided reliable results under specific conditions (Coz, 2008).

Acoustic Doppler Velocimetry (ADV)

Acoustic Doppler Velocimetry (ADV) technology also uses the Doppler Effect to calculate the velocity, but it only provides single point three dimensional velocity (Chanson et al., 2008).

The ADV device is usually composed of three different elements: the conditioning module, the probe and the processor (Figure 2.6). The first one is a cylindrical module mounted vertically, with a down-looking sensor at one of its extremities. The second one is a probe that is connected to the conditioning module. Different kinds of probes make this equipment suitable for measurements under a wide range of conditions. Finally, the processor module is connected to a computer that allows accessing and analyzing the data (Sontek, 2013).

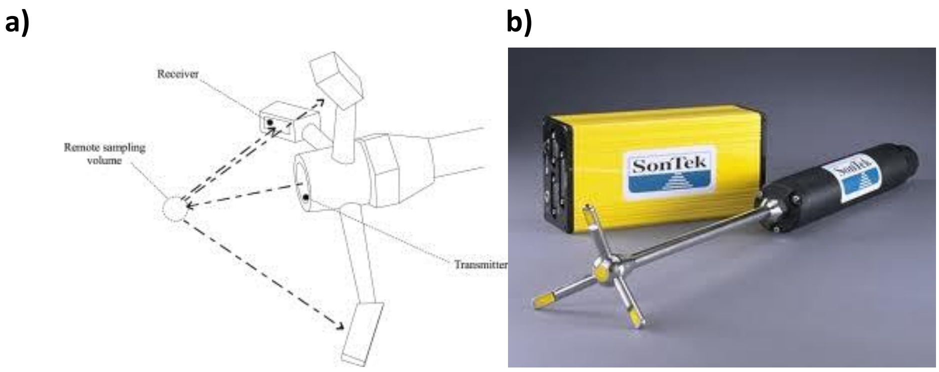

Figure 2.6 – a) ADV probe details; b), Sontek ADV device (Conditioning module, probe and processor).

Morlock & Fisher (2002) presented ADV as an attractive versatile alternative to conventional current meters, especially when dealing with shallow flows. This technique, due to its similarity with ADCP, shares most of its advantages and disadvantages. However the main advantages referred are its simple maintenance, no need for frequent calibration, and high accuracy results.

Both the acoustic Doppler methods (ADCP and ADV) have become important options for routine measurements, due to its safety, speed of measurements, simpleness of installation and relatively low cost (Morlock & Fisher, 2002).

2.5.7. Surface Velocity

Radar Instruments

In this method, a radar sends signals and collects its reflections from particles and roughness of the surface of the stream (Costa et al., 2000). Similarly to the ADCP method (section 2.5.6), software analyzes the shifts in frequency (Doppler Effect) and computes a value for the surface velocity. The process of obtaining discharge from the superficial velocity resembles with the optical method described above.

It's a non-intrusive method, meaning that it surpasses many of the most common limitations of flow measurement techniques (e.g. debris). Wind might cause interference in the surface of the flow. This can be corrected by measuring the wind speed, but at some point it will preclude its use. Nevertheless, it has been proven to be a valid, safe and useful technique for flow measurement.

Optical

This method measures the surface velocity without submerging the equipment (e.g. Rantz, 1982; Kirkpatrick & Shelley, 1975). The flow is observed from above from a stroboscopic device, usually from a bridge, and the motor speed is adjusted in order to obtain synchronization of the angular velocity of the mirror with the water surface movement. This is achieved when there is no apparent motion of the water surface, when observed through the optical meter. The information obtained from the tachometer is then used to estimate the surface velocity of the flow.

When computing discharge, the area-velocity method is used. The surface velocities are converted to mean velocities, usually by considering the mean velocity equal to 80% or 85% of the superficial velocity. This procedure is not precise, introducing inevitable uncertainties to the results.

Optical meters, as many others non-contact methods, can be useful when traditional current meters are impossible to use, for example during floods, which originates high flow velocities and considerable quantities of sediments. However, since it computes velocity based on surface monitoring, it's highly incompatible with wind.

Several other different kinds of optical methods are available, and will be overviewed in section 3, dedicated to flow visualization.

2.5.8. Floats/Drift Tracers

The concept of measuring velocity using floats is quite simple (Figure 2.7). It consists in placing a floating object in the water and measuring the time it takes between two selected cross sections (Hershy, 1995). The float should acquire a constant velocity before starting the measurement and a travel time of at least 20 seconds between the two checkpoints is recommended. Floats of many different sizes and shapes can be used. Oranges are commonly referred as an example of the versatility of this method and its usefulness for emergencies when no other method is available. Also bottles, or longer rods and tubes can be used to reach deeper zones, in order to the velocity of the floats to be closer to the mean velocity of the flow. For wider streams, multiple floats should be used alongside.

Discharge can be obtained by converting surface velocity into mean velocity, using a conversion coefficient (e.g. USBR & USDA, 2001; Rantz, 1982). Therefore, because of the lack of preciseness of this coefficient, along with the probable experimental errors or the influence of wind (more significant for lower velocities), the obtained values aren´t very accurate, which makes this method not suitable for routine data collection.

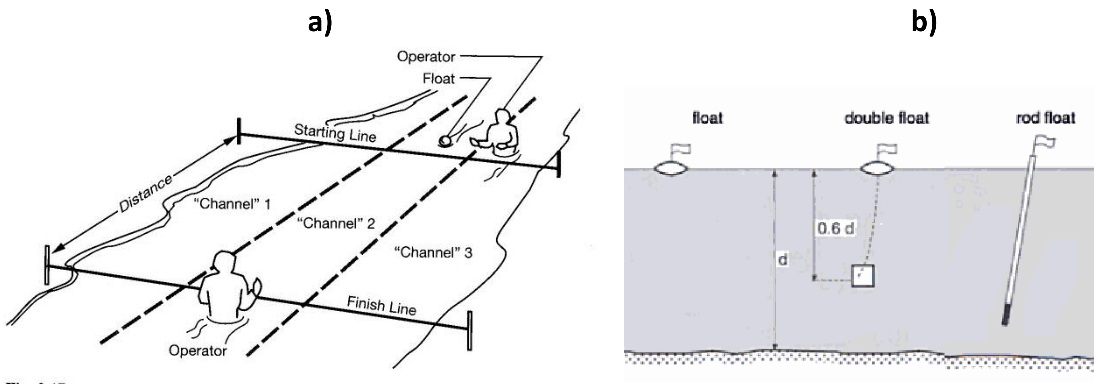

Figure 2.7 - Float measurements: a) procedure illustration (Sanders., 1998); b) different types of floats (Boiten, 2000).

2.5.9. Tracer Methods

This technique consists in injecting a substance into the water flow, generally referred as "tracer", and in measuring its movement. Thus, it's an indirect method (the tracer movement is measured, instead of the flow itself) that relies on the assumption that the motion of the tracer is exactly the same as the movement of the fluid.

There are two different approaches in this tracer technique: tracer-time-of-travel and tracer-dilution. The first one is based on the tracer time of travel and the second one is based on the degree of dilution observed.

When the tracer is added to the flow, it starts dispersing in all three directions. An initial mixing period ends when full mixing is complete for the vertical and lateral directions. Then, the longitudinal mixing goes on indefinitely, because it is not restrained. Full lateral and vertical mixing is crucial, especially for the success of the tracer-dilution variation (Hubbard et al., 1982).

Tracer methods provide information about mean velocity (tracer velocity) or discharge (tracer dilution). It’s however impossible to infer about vertical velocity profile with this technique. Nonetheless, this is not a constraint when dealing with shallow flows, making this technique a powerful way to surpass most difficulties when measuring this kind of flow.

Recent development of stable fluorescent dyes and more advanced fluorometers that can detect chemicals in very low concentrations helped increase the importance and accuracy of this technique (Tauro et al., 2012). Therefore, if performed properly by following all the recommendations and procedures available (e.g. USGS recommendations), it can provide very accurate and reliable results. It highly depends on the equipment used and experience of the operator. It can be a very useful method, especially under conditions where other techniques are not appropriate (e.g. low water depths, debris that damage equipment, excessive turbulence, inaccessible flow, unsteady flow, etc.). Tracers also have the advantage of not obstructing the flow, thus not causing head loss.

Tracer Types and Desirable Characteristics

There are many available types of tracers that can be used, each one of them with its own characteristics and, consequently, different advantages and disadvantages. The used tracer should be wisely chosen from the available options, which can be limited by many constraints, such as price, readiness of use, environmental impacts or quality of visualization.

An “ideal” tracer has the following characteristics:

- Availability and environment
    - Inexpensive
    - Harmless
    - Low toxicity
- Visibility (detectability)
    - Unique spectrum
    - Strongly visible (fluorescent)
    - Initially absent from water flow (or in low concentrations)
- Properties (properly follow flow motion, lower velocity lag, low tracer loss)

- Stability - not decomposable (avoid chemical reactions with other elements that might be present)
  - Chlorine quenching
  - Photochemical decay
- Low adsorption and absorption (minimize tracer loss)
- Density similar to water
- High water solubility
- Low agglomeration (compromises assumption of following the flow)

In brief, a tracer should blend perfectly into the flow, accurately replicating its movement, while allowing proper visualization and quantification, without any limitations to its applicability (e.g. price, pollution, etc.). Although there are no ideal tracers, this technique can still be used with quite good results, if the proper tracer for the objective and nature of the experiment is selected (Mei, 1996).

The quantity of tracer to be used depends on discharge, downstream distance to the measuring site or expected loss of tracer. There are formulas, especially for long distance travel time measurements, for determining the quantity of tracer that has to be added to the flow (Hubbard et al., 1982). There must be a balance between adding enough tracer to allow proper visualization and, on the contrary, not to add tracer in excess that might change the flow characteristics.

There are many types of tracers which include electrolyte tracers (e.g. salt solutions), dye, magnetized tracers or radioactive tracers. The latter one isn't used very often, due to complications with the handling of radioactive materials. Several other tracers have been used and experimented with, often for qualitative and flow visualization purposes (section 3), instead of directly for flow velocity measurements, such as the hydrogen bubble (section 3.2.2) or the thymol blue technique (section 3.2.3).

Despite sharing the same principle, each tracer has its own characteristics and requires different equipment and methods for its detection.

Dye tracers can be tracked visually (only in the tracer velocity method) or alternatively by using a fluorometer, which improves accuracy. There are plenty of options of substances that can be used as dye tracers. Experiments have been made with different kinds of dyes including Rhodamine (BA and WT), Fluorescent dyes (Fluorescein) or even regular food dyes (Amaranth 85, E 123) (Rummel et al., 2002). Fluorescent dyes are becoming more popular, due to its visibility even in low concentrations (Tauro et al., 2012).

Another option is to use electrolyte tracers (e.g. USBR & USDA, 2001; Shi et al., 2012; Tingwu et al., 2005). This is often referred to as the salt-velocity method and consists in the addition of a salt solution to the flow inducing a change in the electrical conductivity properties of the water. The passage of the tracer is revealed by establishing and monitoring an electrical current in the sampling section. The electrical current vs. time graphs allows the detection of a peak that corresponds to the passage of the tracer (salt increases conductivity and lowers resistivity of the water).

Similarly, time travel of radioactive isotopes or magnetized materials tracers is measured downstream by using radiation sensing equipment.

Finally, the use of heat tracers, which is the scope of this thesis, can be accomplished, for example, by the use of thermographic cameras.

Tracer-Velocity

The tracer-velocity principle is similar to the one explained for the floats technique which can also be referred to as drift tracers. However, instead of a solid object, the tracer used is also a fluid that participates in the normal fluid processes, getting mixed and transported within the flow through convective and diffusion phenomena's (Figure 2.8). Therefore, the procedure is to measure the time that the tracer takes to travel between two sections. The distance between both sections is then divided by the measured time, in order to compute velocity.

In most cases, the velocity of the leading edge is measured. This velocity does not correspond to the mean flow velocity. Instead, it corresponds to the maximum velocity since the tracer will follow the highest velocity path. Thus, the obtained velocity must be multiplied by a coefficient to obtain the mean velocity, and this introduces an error in the estimation.

The tracer-velocity method has the advantage of requiring small quantities of tracer, when compared to tracer-dilution method (continuous injection). This method can also be used for long distance measurements (sampling section over 50 km downstream from injection point). In this case, dye losses along the way can be significant, thus more dye is necessary.

a) **b)**

Figure 2.8 - Dye tracing field experiments examples: a) Rhodamine (Global Underwater Explorers, 2013); b) Fluorescent dyes (Fondriest, 2013)

Tracer-Dilution

In the tracer-dilution method, discharge is computed by analyzing the degree of dilution of an added tracer (concentration) (Hershy, 1995). It consists in the addition to the flow of a known quantity of a highly concentrated solution of either dye or salt. In a measuring section downstream a detection device is used (fluorometer for dyes and electrodes for salt, as described above).

Discharge is computed from the concentration balance between the injection and sampling section (Rantz, 1982). Therefore, complete vertical and lateral mixing in the sampling section is assumed and accuracy of results are highly dependent on it. The amount of losses of tracer (exchanges of tracer between flow and soil such as adsorption or salts dissolved from the soil), also influence accuracy. Thus, there is an optimum travel time and length that ensures proper mixing without significant losses. However, for short distances dye loss is usually not significant.

The injection of tracer can be done in a single slug or by a continuous injection. Figure 2.9 shows the concentration versus time graph in the sampling for both types of injection. In the latter case, the graph exhibits a "plateau" because the tracer is injected during a certain period of time, inducing a constant concentration in the sampling section downstream. In this case, discharge is computed from the knowledge of the injection conditions (volume and concentration) and from the integration of the concentration versus time curve (measuring section).

Besides facilitating the injection process, choosing the slug injection option also has the advantage of reducing the amount of tracer used.

It's important to refer that no geometry nor stage measurements are needed to compute discharge, what can be a strong advantage over other methods, especially if the stream is inaccessible (e.g. measurements in mountain torrents).

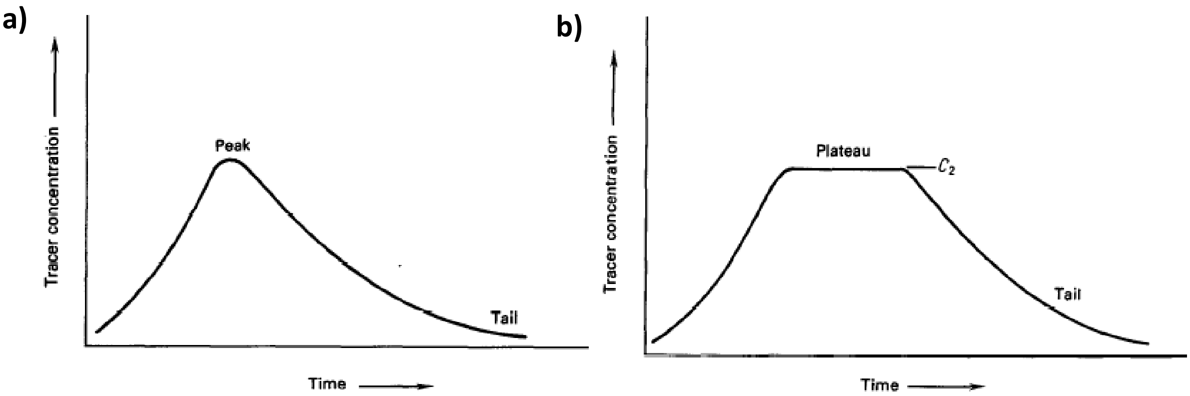

Figure 2.9 - Concentration vs. time graphs at the sampling section: a) slug injection; b) continuous injection (adapted from Kirkpatrick & Shelley, 1975).

Correction Factor (α) from Surface to Mean Velocity (Tracers)

When tracers are used for quantitative estimation of mean flow velocity of the flow by measuring the time of travel of the leading edge, what's truly being measured it's the surface velocity. In order to obtain the mean velocity value, this value must be multiplied by a correction coefficient, usually referred to by the Greek letter α (Li et al., 1996). However, due to the intrinsic relation between flow velocity and many other variables and conditions such as turbulence (defined by the Reynolds number), slope, flow variation with time (steady or unsteady) or sediment content, the determination and systematization of this calibration coefficient is still a challenge for researchers. Added complications appear in field applications of tracer techniques, with even more unknown variables and presence of rocks and vegetation.

Across literature, different authors presented results obtained for a wide range of conditions. Some discovered relations with sediment transport, others variation with slope or even with the Reynolds number (e.g. Zhang et al., 2010; Dunkerley, 2001). Mean correction factor values fluctuate between 0.53 and 0.67. This illustrates the difficulties, dispersion of results and even contradictions faced by many researchers that, in the last three decades, struggled to define this coefficient. In the present thesis, the value proposed by Li & Abrahams (1996), $\alpha = 0.67$, will be used, as it's the commonly recommended value.

2.6. Final Comment on Hydrometry

A wide range of powerful and accurate techniques is now available. The main challenges for hydrometry (Coz, 2008) are now to maintain and improve data quality, without increasing the need for more resources (e.g. cost, human resources) for its collection. Standards and goals should however be achievable and realistic. In addition, environmental concerns have also become an important topic, (e.g. the use of dyes can be have a negative environmental impact).

The knowledge of the multiple available techniques and the awareness of their limitations, applicability and inevitable uncertainties is crucial for the selection of the most adequate technique and measuring site. The use of various techniques simultaneously (as complement or to fill each other's limitations) and the repetition of the measurement process (if possible, accordingly to the quickness of the technique) are important in order to minimize potential errors and uncertainties.

3. WATER FLOW VISUALIZATION

3.1. Initial Considerations

Some of the previously referred methods illustrate the thin frontier between flow measurement and flow visualization techniques. In fact, by being able to visualize the flow, it's possible to infer about velocity fields. With the recent developments in imaging technology, significant improvements and results have been achieved from the use of techniques such as the Particle Imaging Velocimetry (PIV), Particle Tracking Velocimetry (PTV) or the Planar Concentration Analysis (PCA). There is, however, still a long way ahead, since it's complicated to interpret data involving turbulence, complicated boundaries, viscosity or shock wave effects.

There are mainly three different approaches on which flow visualization is based (Merzkirch, 1974). The first one consists in adding a different material to the flowing fluid and then using the referred optical imaging methods to track its motion. Therefore, the tracer method for flow visualization previously referred in section 2.5.9 belongs to this category. It's considered an indirect method since the results are obtained by measuring the tracer motion instead. The assumption is that the tracer and fluid motion are exactly the same, which may not be exactly true, especially in unsteady flows.

Another approach relies in the fact that fluid density is a function of the refraction index. Thus, optical methods are sensitive to these variations in density and allow to obtain a visual pattern from which quantitative or qualitative data can be obtained. They are non-disturbing methods and some examples include shadowgraphy, schlieren or interferometry.

Finally, the last approach consists in exposing part of the flow to energy in the form of heat or electrical discharge in order to mark them and make them visible through the use of optical methods (thymol blue, hydrogen bubbles). The method described in the present thesis is a good example of this kind of approach, since it consists in heating the water and then using a thermographic camera to track its motion. However, in the case of adding hot water to the flow, this same technique can be classified as a heat tracer technique. Either way, its principle is to track the heat downstream.

It's important to emphasize that the flow patterns obtained with these techniques are quite difficult to analyze and to model, mostly due to the complex processes that are involved, even using powerful computers. Flow visualization can, however, provide useful qualitative and quantitative information about flow properties, such as velocity, frequency or density. It has many applications, especially for analyzing velocity, waves, mixing processes, vortices, eddies or wakes.

A noteworthy fact is that these flow visualization methods are widely used, not only in liquid flows, but also in gases.

In the next paragraphs, the most relevant flow visualization techniques for this thesis purposes will be overviewed.

3.2. Flow Visualization Techniques

3.2.1. PIV and PTV

In the Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) techniques, a flow homogeneously seeded with particles is illuminated by a sheet of light. Using an optical system, the positions of the particles at consecutive moments are recorded and its displacements are analyzed. The result is a planar map with instantaneous velocity vectors that represent the velocity field of the flow (Figure 3.1).

The main difference between PIV and PTV is the obtained image density. In PTV method, a single particle can unambiguously be tracked (Bradley et al., 2002). On the contrary, if the distance between particles is too short, it's no longer possible to track each particle individually, and the matching of pairs of particles is determined statistically. Thus, in the PIV method, a not well defined region emerges, where the displacements of particles are obtained through a statistical method and a spatial correlation analysis is carried to obtain the velocity field, based on a continuity equation (number of particles remain the same). Because the motion of more particles is studied, PIV technique provides more information than the PTV.

Although it's not a new technique, its use has increased significantly in the last years due to the easier access to charge-coupled device (CCD) cameras and more powerful computers. Thus, it has become a well-established as a non-intrusive technique for flow measurement and visualization of a whole field (e.g. Nobach & Tropea, 2005, Meinhart et al., 2000). However, this technique still requires a relatively complex and expensive set up (require high power lasers), hardly suitable for experiments in the field, due to its limited portability.

3.2.2. Hydrogen Bubbles

By using an electric current to induce an electrolysis in the water, hydrogen bubbles can be produced to act as visible tracers. The bubbles created, due to their dimension, adequately follow the motion of the flow, and are another suitable option for flow visualization. The bubbles are created around the wire and are swept by the flow, following its motion. The diameters of the bubbles are similar to the diameter of the wire and are visible by illuminating the stream. Due to flotation, the bubbles show tendency to ascend. Lu & Smith (1985) first presented the technique as a suitable method for the determination of the local velocity behavior and how turbulence properties could be evaluated.

3.2.3. Thymol Blue

Thymol blue is often used as a pH indicator, as it allows establishing a pH range (e.g. Merzkirch, 1974; Merzkirch, 2007). It can either be red, yellow or blue accordingly to the pH of the solution it contacts with. Relying on the creation of hydrogen ions induced by electrolysis to increase the overall solution pH, the thymol blue changes color to blue near the electric wire. By using electric pulses, a well-defined blue line is clearly visible and allows visualization of velocity profiles.

3.2.4. Bubble Image Velocimetry (BIV)

The Bubble Image Velocimetry (BIV) is often considered a variation of the PIV technique (Lin et al., 2008). BIV consist in tracking the liquid-gas interfaces present in the flow (e.g. air bubbles), instead of solid particles used in the PIV. Concerning the illumination and obtainment of the images, the Shadowgraph method is used. A light is placed behind the flow and the shadow of the bubbles are captured and consequently processed with PIV software to correlate its positions in consecutive images to construct the vectorial velocity field. This procedure dismisses the use of expensive high power laser system, facilitating its implementation and use in the laboratories.

This technique aims at the visualization of aerated bubbly flows. For example, as the bubbly aerated regions of the flow are complex to analyze with the PIV method (problem with uncontrolled scatter of laser light), BIV has been used as a complementary technique to fill this flaw (Figure 3.1; Ryu et al., 2005). The density and size of the bubbles have to comply with seeding requirements in order to ensure that they can be identified and separated for the analysis.

Hillier et al. (2010) also used similar procedures, however successfully using the classic hydrogen bubbles principle as a seeding medium.

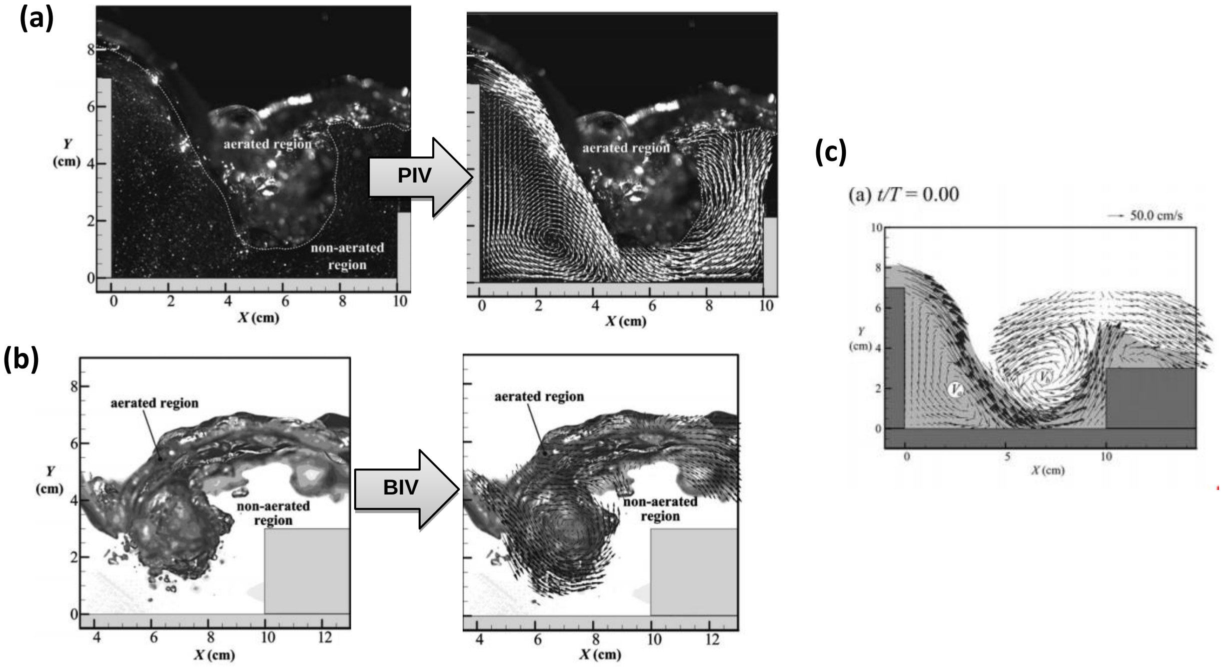

Figure 3.1 - PIV and BIV as complementary techniques: a) sample image obtained by PIV and its corresponding velocity field; b) sample image obtained by BIV and its corresponding velocity field; c) resulting velocity field from both PIV and BIV analysis (adapted from Lin et al., 2008).

3.2.5. Planar Laser Induced Fluorescence (PLIF)

In the Planar Laser Induced Fluorescence (PLIF) techniques (Ferrier et al., 1993), a laser light sheet is used for exciting fluorescent dyes molecules (usually Rhodamine). As a result, the molecules acquire a higher electronic energy state. Thus, as the energy is released, fluorescence of the molecules is induced. The resulting fluorescence is recorded and, after calibration, its intensity can be related with temperature or dye concentration. The obtained maps can be used for flow visualization purposes (Crimaldi & Koseff, 2001).

3.2.6. Planar Doppler Velocimetry (PDV)

Similarly to LDV technique (section 2.5.3), Planar Doppler Velocimetry (PDV) or Doppler Global Velocimetry (DGV) also uses the Doppler shift of the backscatter from the particles to compute the multidimensional velocity field. However, instead of single beams, DGV uses a laser light sheet to illuminate a whole area of the flow (Nobes et al., 2004).

It's a relatively new technique that has some advantages over the PIV technique (Samimy & Wernet, 2000), such as allowing higher speed flow measurements, higher resolution analysis, velocity analysis without directional ambiguity, or possibility of using smaller particles (improved tracer characteristics). However, its experimental setup is rather complex, what is considerable limitation for DGV to become an accessible alternative to other methods.

3.2.7. Planar Concentrartion Analysis (PCA)

Rummel et al. (2002) developed a method for dye tracing analysis, where recorded video images were used to obtain dye concentration values by statistically analyzing color intensity (Leandro et al., 2012). MathLab is used to convert pixel intensity to concentration values, according to a transfer equation algorithm, thus creating a concentration map. The process involves going through several steps to improve image quality and through proper calibration of the transfer function. Because this technique is very sensitive to illumination variations, the experimental set up involves the use of sheets in order to ensure good and homogeneous uniform illumination of the camera's field of view, making it only suitable for lab experiments (Figure 3.2).

This technique, when compared to other flow visualization methods such as the PIV, requires a simple and affordable set up and can be a valuable option for shallow flows dye tracing analysis.

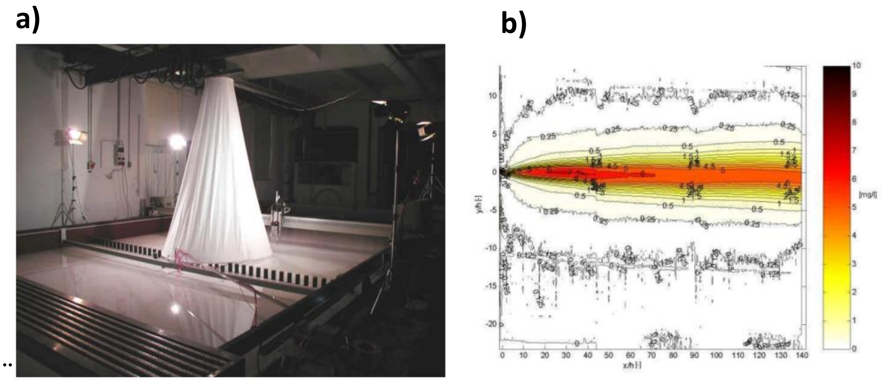

Figure 3.2 – a) Sheet to ensure uniform illumination; b) Distribution of the time-mean concentration, evaluated with the PCA (Rummel et al., 2002).

3.3. Infrared Technology

3.3.1. Thermography

Infrared (IR) represents the electromagnetic radiation with wavelengths between 0.74 microns and 1000 microns. This represents the zone in the electromagnetic spectrum (Figure 3.3) between the visible light and microwaves and humans can perceive it as heat. Every object above the absolute zero in temperature scale (−273.15°C) emits infrared and its emittance increases with temperature.

Thermography is a technique for detection and measurement of the radiated thermal energy (FLIR, 2013). A special lens is used to collect all the infrared radiation in the camera's field of view which is converted to digital signals. These signals are then processed to obtain an image that can be displayed in a monitor, associated to a grey or color scale. After calibration, thermographic cameras can also provide temperature values, depending on the used software.

However, not the entire IR spectrum is visible through thermography. Most common IR cameras can detect radiation in the LWIR band (long-wavelength infrared - 8μm-14μm), which include most applications at ambient temperatures.

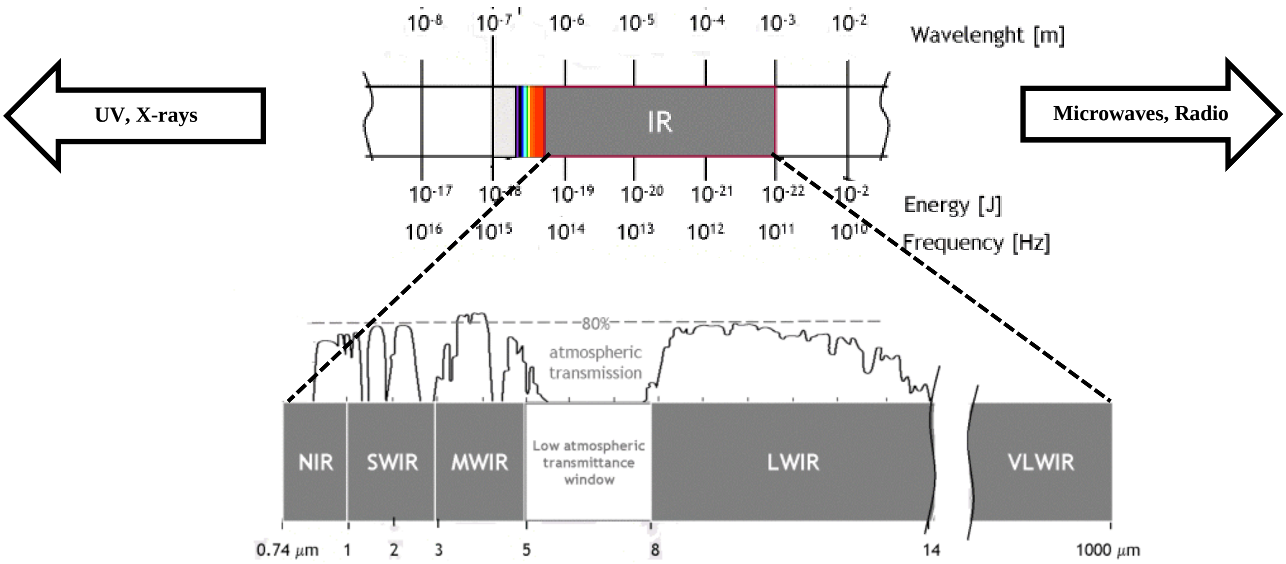

Figure 3.3 - Infrared radiation in the electromagnetic spectrum (adapted from MVIM, 2013).

It’s important to note that glass is opaque in the long-wavelength infrared (LWIR) band, blocking the radiation emitted by the objects behind it. In addition, emissivity is a physical property of materials that describes the efficiency of how it radiates. Thus, two materials with different emissivity may appear differently in thermal imaging, despite having the same temperature. It’s also important to emphasize that thermographic cameras detect the energy that radiates through the surface, not the temperature of the object itself.

Due to the recent reduction of costs of these cameras along with the increased portability, thermography application range has increased considerably. It has been used extensively as night vision technology in military and law enforcement operations (Figure 4.4). It is also becoming a consolidated technique for uses in industry, building inspections and electrical systems diagnosis, mainly because it’s a safe and accurate method of detecting problems (Page et al., 1992). It is also becoming an important tool for uses in research in diverse fields of knowledge, since it provides an effective, fast and accurate method of monitoring temperature.

3.3.2. Applications of Infrared Technology in Hydraulics

Along the decades, infrared technology has been occasionally used in hydraulic studies. Due to the reason referred in the previous section, its applications in water resources, hydrology and soil and water preservation have recently been developing significantly.

One of its major focus is large scale aerial thermal scans. These can provide valuable information for various purposes. For example, by obtaining sequences of high resolution temperature maps (thermal gradients) from oceanic waters, it's possible to infer about near surface velocities, as described by Chen et al. (2008), Chen et al. (2012) and Veron et al. (2008).

Another effective use is to scan watersheds to search for groundwater inflows (seeps) and karst hydrogeology formations (e.g. Jester, 2000; Campbell et al., 1996). These are easily identified because groundwater is released with different temperature than surface waters (e.g. during winter, groundwater is warmer than surface water, exposed to low atmospheric temperatures), thus appearing with a different color intensity in infrared images (Danielescu et al., 2009). In addition, these remote sensing techniques can also provide other types of relevant hydrological information (e.g. water quality indicators, identification of local pollution sources, characterization of pollutant movement and dispersion) (Rayne & Henderson, 2004).

However, the use of infrared thermography for these purposes still has to overcome some weaknesses such as the influence of interference originated by unwanted emissive radiation, thermal stratification problems, or thermal boundary layer effects.

The use of IR thermography for quantitative flow measurements hasn't been extensively explored yet, and its capabilities have yet to be studied. Some successful examples can already be found in the literature. Below some examples of research works are presented, which are relevant for the present technique due to their similarity of procedures or because they share a similar principle.

Thermal Sensors

Sensors using heat related principles (Ashauer et al., 1998) are frequently used in flow measurements in conduits. Measurements can be based on heat losses considerations (e.g. thermal anemometers – section 2.5.3). Instead, using the thermal transfer principle, by measuring the energy and the resulting temperature increment, it's possible to compute the flow discharge (e.g. calorimeters). Finally, some sensors are based on the thermal time of flight principle, where heat pulses are generated and used to compute velocity. The present thesis approach to measure velocity is similar; however, it's implemented on larger spatial and temporal scales.

Microfluidic devices application

A velocity measurement technique employed in microfluidic silicon devices (micro-electromechanical system) has been presented by Chung & Grigoropoulos (2003) and Liu et al. (2005). Due to their small dimensions, most flow meters are not adequate. Thus, this technique is presented as a high prospect solution for this problem. The fluid is heated by a pulsed infrared laser beam and relies on the fact that silicon is transparent for IR wave lengths and consequently thermography can detect heat gradients through the silicon. The results showed an accuracy of around 10% on mean velocity measurements. The acronym used to refer to this technique was ITV (Infrared Thermal Velocimetry).

Turbulence visualization

Using similar procedures, in a wide open flow flume, Liang & Chong (2011) studied the feasibility of using thermography to visualize turbulent mixing processes in shallow flows. The hot water was injected behind a cylinder that originated the turbulent structures (wake and vortices). It has been concluded that the results agree with past studies using traditional techniques.

Solute transport assessment

A similar technique to the one presented in this thesis, involving slug hot water addition to the flow and infrared thermography, was presented by Schuetz et al. (2012). The technique was applied in the field to wetlands in order to study solute transport processes. Mean flow velocity, dispersion and dominating flow paths could also be remotely detected in this work. However, in contrast to the technique described in the present thesis, it dealt with lower velocities and the temperature values provided by the camera allowed a different approach, namely for the analysis of cooling effects (advection, dispersion and conduction).

4. MATERIALS AND METHODOLOGY

4.1. Experimental Setup

The experiments were conducted in a small laboratory in the Texas Tech University Department of Civil and Environmental Engineering, in Lubbock, Texas (USA). The experiments are easy to prepare and are schematized in Figure 4.1 and Figure 4.2.

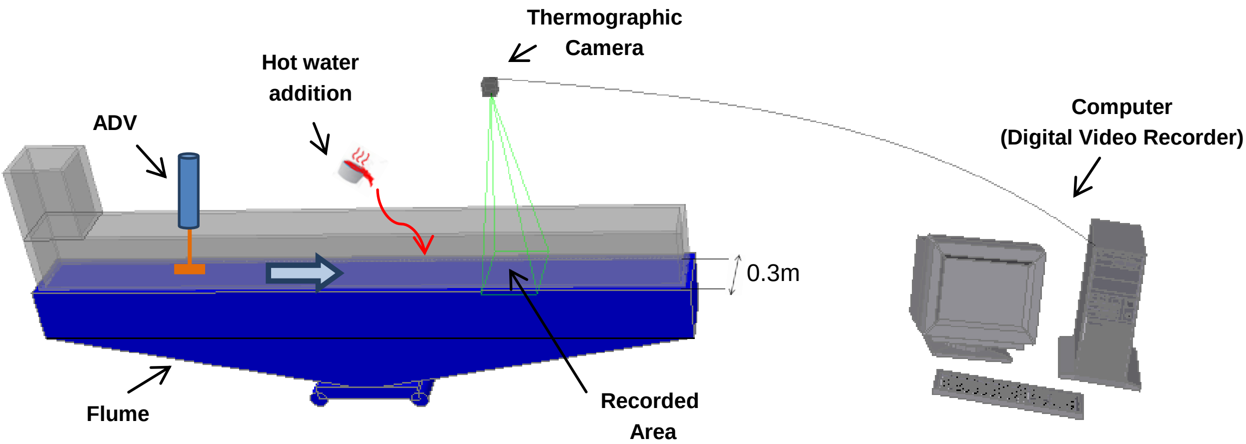

Figure 4.1 - Schematization of the experimental setup.

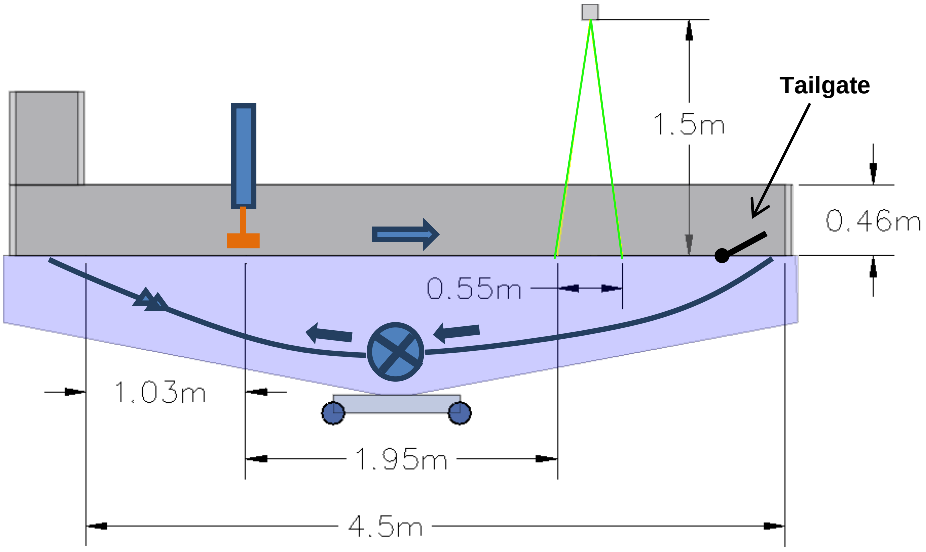

Figure 4.2 – Scheme of the hydraulic circuit and dimensions of the experimental setup (not to scale).

4.1.1. The Flume

For the experiments, a flume designed by Engineering Laboratory Design Inc. was used and provided a channel 0.3 m wide and 4.5 m long (Eldinc, 2013). It was mainly developed for working as a multipurpose demonstration channel for support of academic courses. Therefore, different accessories and devices can be easily installed such as weirs of different shapes, meters or even conduits.

The flume bed and walls are made of acrylic Plexiglas (leak proof joints and good impact resistance), thus impermeable, smooth and transparent (Figure 4.3). The slope is easily adjustable by a motorized jacking system. Similarly, the end of the flume has an adjustable tilting plate that allows depth control. Upstream, a head tank is available, for inducing pressurized flow, when the conduit circuit is installed. The flume operates as a self-recirculating circuit with integrated pumps and is controlled by valves that can be regulated by the user. The full specifications, adapted from manufacturer website, are presented in Table 4.1.

Table 4.1 - Flume specifications.

Maximum Flow Rate	360 l/s
Slope Range	-4% to 12%
Overall dimensions	2.28 m × 0.90 m × 4.95 m
Dry Weight	612 kg
Power	0.56 kW

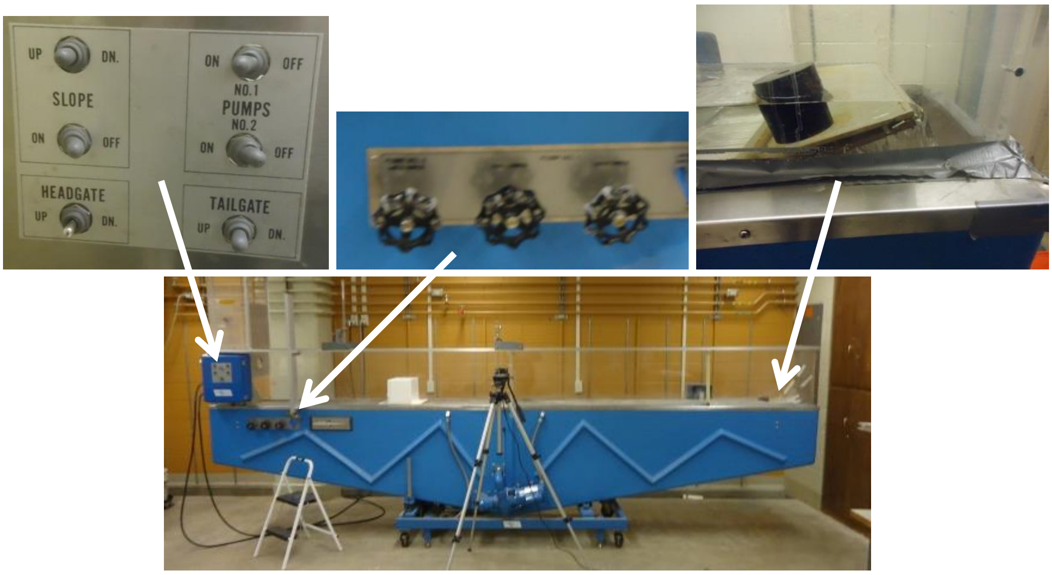

Figure 4.3 - Flume and details of the flume controls (slope and pump controls, valve controls and tailgate).

4.1.2. Imaging System

A FLIR PathFinderIR-LE infrared camera was used in the experiments. FLIR is a leading worldwide manufacturer of innovative imaging systems**.** This camera was designed for night vision applications, and is often used in law enforcement and emergency vehicles, since it allows vision under total darkness conditions. It also permits to see through smoke. In addition, its compact size and the Vision Enhancement System makes it suitable as an auxiliary driving instrument, increasing road awareness and allowing faster reaction to upcoming hazards (FLIR, 2013). This camera has also been used for surveillance purposes (Figure 4.4), since it offers a wide field of view (35ºH × 27ºV). The commercial price of this thermographic camera model in March 2013 was around 1900 €. The full specifications of this camera are given in Table 4.2.

Table 4.2 - Camera specifications (FLIR, 2008).

Model	ThermoVision®PathFindIR -LE 334-0001-00-10-LE
Sensor Type	Uncooled microbolometer
Field of View	36º H × 27º V
Spectral Band	8-14 µm
Resolution	320 × 240 pixels
Time to Image	< 2sec
Focal Length	19mm
Power Consumptiom	2Watts (nominal)
Operating Temperature	-40ºC to +80ºC
Output Frame Rate	30 Hz (NTSC) or 25 Hz (PAL)
Dimensions	58 mm × 57 mm × 72 mm
Weight	0.4 kg
Price (March 2013)	Around 1900 € (2500 USD)

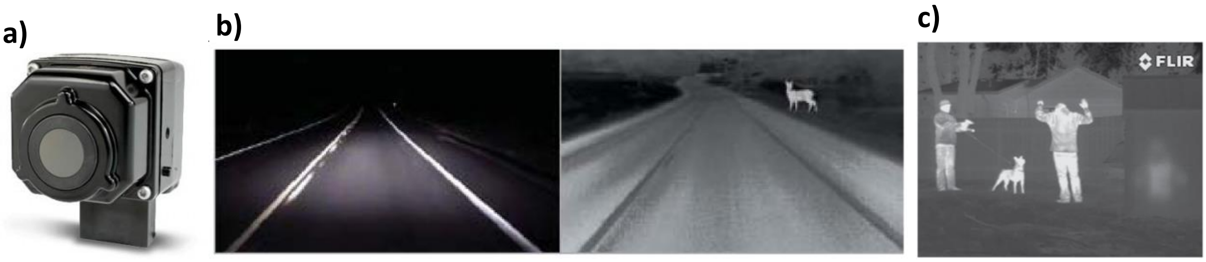

Figure 4.4 - a) FLIR Camera; b) comparison between road visibility with regular headlights; c) example of law enforcement use (FLIR, 2008).

In the laboratory experiments, the camera was connected to a Digital Video Recorder (DVR) system, as described in section 4.1.3, which allowed the recording of a 30 frames per second footage of 320 × 240 = 76800 pixel images.

The area of flow captured by the camera decreases with its proximity to the channel while the spatial resolution increases. Thus, a trade off had to be made, and the camera was hanged 1.5 m above the flume, resulting in a recording area of 42×55 cm^2.

4.1.3. Digital Video Recorder System (DVR)

The digital video recorder (DVR) system used in the experiments was developed in 2004 (Cleveland, 2007). The hardware for the system is comprised of an end-user PC computer and ancillary equipment (DVR cards and cameras) with the specifications listed in Table 4.3. Figure 4.5 shows a DVR card and the back of the computer, where the three rows of four connections are visible. A screenshot of the Swann DVR software is also shown. Along the right edge and along the bottom there are some controls which allow the access to the settings menu where the frame rate or the time stamp can be changed. It's also visible the multiple channel feature (screen divided in four) which emphasizes the fact that the software has been developed for surveillance use (e.g. banks, smart communities, traffic management units, medical systems, educational systems or armed forces) (Swann, 2003).

Table 4.3 - DVR specifications (adapted from Cleveland, 2007).

Motherboard	PC Chips M848A
Processor	AMD K7 Sempron 2800 (1.2 GHz)
RAM	512 MB DDR 400
Hard Drive	200GB Seagate Ultra ATA/100 7200
CDROM	Nec CDR 1800A
FD	1.2 MB IDE (generic)
DVR Input 1	Swann PC DVR-4 TD-3004F6.4
Video Input	PathFinderIR-LE FLIR camera
Power Supply	Allied AL400-ATX 400W
Chassis	Antec 8U ATX Tower
Op System	Microsoft Windows 200 SP1
DVR	Swann PC-DVR-4-Net V4 (2005_0707)

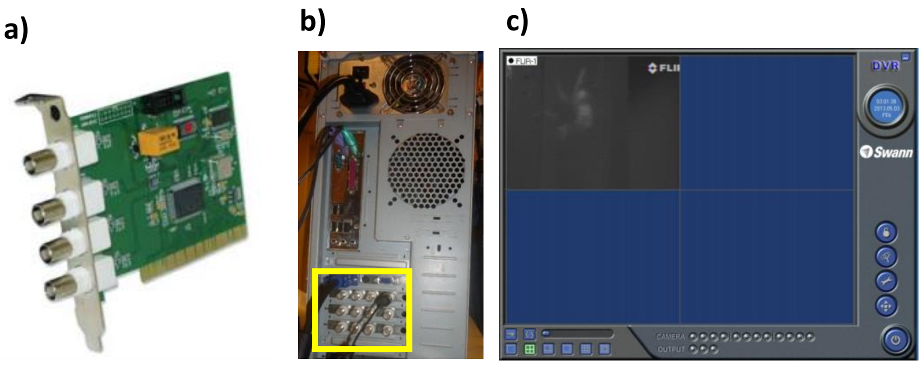

Figure 4.5 - DVR system: a) DVR hardware; b) back of the computer; c) screenshot of the Swann DVR software.

4.1.4. Velocity Measurements (ADV)

For comparison purposes, additional velocity measurement equipment was required. Thus, a SonTek/YSI 16-MHz MicroADV (Acoustic Doppler Velocimeter) with a 2D side-looking probe was used in the experiments (Figure 4.6). This probe is the most adequate option when dealing with shallow water depths. It allows velocity measurements in channels as shallow as 3 cm and as narrow as 5 cm (SonTek, 2008). Table 4.4 shows the full specifications of the ADV.

The setup of the equipment was simple since it required no further calibration. SonTek Horizon ADV software was used for data acquisition from the device. Velocity measurements were obtained by computing the average from 600 samples.

The air bubbles originated by the inevitable turbulence of the water flow were sufficient to reflect the acoustic signals, allowing the ADV to detect and compute velocity. During experiments, the signal-to-noise ratio (SNR) indicated by the SonTek software was around 40, which is above the SNR recommended minimum value (15), thus the flow was well seeded and measurements were reliable.

Table 4.4 - ADV specifications (adapted from SonTek, 2008).

Sampling rate	0.1 to 50 Hz
Sampling volume	0.09 cm^3
Distance to sampling volume	5 cm
Resolution	0.01 cm/s
Velocity range	1 mm/s to 2.5 m/s,
Programmed velocity range	3, 10, 30, 100, 250 cm/s
Accuracy	1% of measured velocity, 0.25 cm/s
Max Depth	60 m
Input Voltage	12-24 VDC
Power Consumption	2.5 to 4 W

Figure 4.6 - Different components of the used ADV: a) conditioning module; b) processor; c) 2D side-looking probe.

4.2. Procedures

Because the present work consists in the development of a novel technique, the experimental work had to go through a *trial and error* process in order to select the most effective setup and procedures. The different phases of this process will be outlined in this section.

Regarding the positioning of the camera, it was easily observed that the most favorable option was undoubtedly to hang the camera over the flume, perpendicularly to the flow. An attempt to visualize the flow from the side was quickly abandoned, because the acrylic material from the flume is opaque to thermographic cameras and consequently blocks the IR radiation. Placing the camera pointing upstream obliquely to the flow was also not a good option because, besides the distortion originated, reflections from both the acrylic walls and the water surface compromised the quality of the recordings. This latter solution, despite not being the most efficient, can still be used in situations where placing the camera perpendicularly to the flow is complicated. As an example, in a field application of a similar technique, (Schuetz et al., 2012) recorded the flow by installing the camera downstream from the analyzed area, and then applied a distortion to the images in order to be able to analyze them. In addition, in field measurements or in wider flumes, the acrylic reflections are not a problem.

In order to obtain a spatial reference, before each experiment, hot water was spread along the full width of the channel, highlighting the channel bed (Figure 4.7) and allowing the identification and measurement of the channel width (known distance). Alternatively, any other two temperature markers (IR leds or an object of a material with a different emissivity or temperature) separated by a known distance would allow the spatial calibration of the obtained images (necessary to compute velocity).

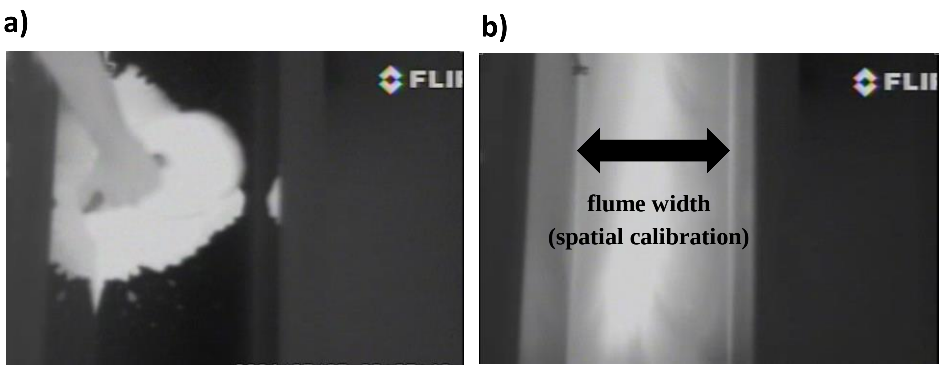

Figure 4.7 - Spatial calibration for the experiments: a) hot water spread; b) flume width.

The FLIR camera, when turned on inside the room at ambient temperature, revealed practically no image resolve. While down looking at the flow, it was possible to identify a moving mass of heated water. An example of the obtained images is presented in Figure 4.8. Brighter colors represent higher temperatures while lower temperature surfaces are darker. It clearly exhibits the downwards movement of the heated water. Due to high flow speeds, the image faded fast.

At an early stage, by comparing the velocity of the heated water mass with the velocity obtained through the use of floats, it was possible to confirm that these procedures could provide an estimation of the flow surface velocity.

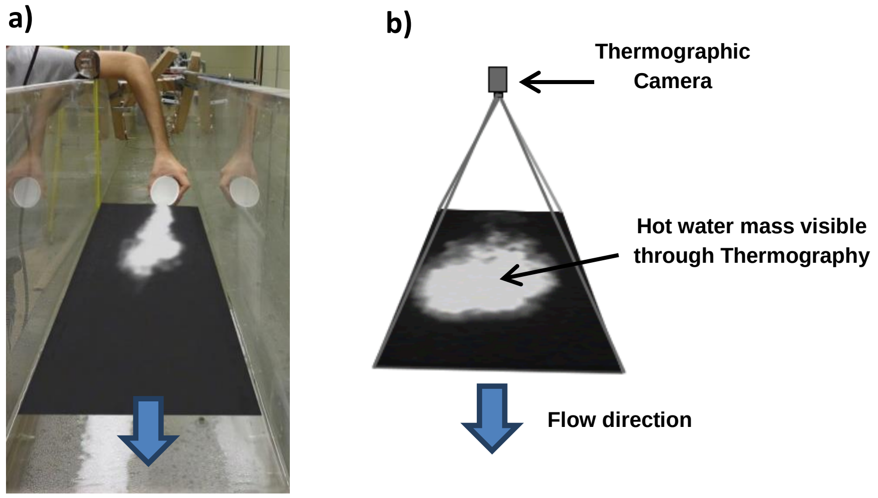

Figure 4.8 – Example of the obtained images and schematization of the procedure used in the experiments for adding the thermal tracer (hot water) to the flow.

The obtained surface velocity was multiplied by a correction factor α=0.67 (Abrahams & Li, 1998), usually used in tracer methods for converting from the surface velocity to the mean flow velocity (see section 02.5.9).

In order to validate the experiments as a proof of principle of the technique, sets of experiments were conducted simultaneously with an ADV (section 4.1.4), which is considered a well-established and trustworthy velocity measurement technique.

The next step was to test different water heating methods and to try to improve the water heating process. The tested methods are described in section 4.4. Similarly, some notes on the image processing phase are presented in section 4.3.

4.3. Images Interpretation

The image interpretation phase, due to its direct influence on accuracy, is crucial for the success of this technique. This process has high resemblances with the dye tracing technique, where the progression (time of travel) of the dye cloud is measured visually. However, for dyes, these measurements are usually made using stopwatches and human reaction errors are likely to be significant. In the present technique, this kind of errors is reduced due to the use of recorded images. The video player capabilities (e.g. start, stop, move forward, rewind) allow a precise frame by frame analysis that would be impossible to accomplish with human reaction time uncertainties. Furthermore, it also allows more time and tools to properly infer about the heated water mass delimitation (identification of the leading front).

For mean flow velocity estimation purposes, there are two options to analyze the downstream motion of a mass of tracer. Some authors track the center of mass (Kirkpatrick & Shelley, 1975) while others assume that the leading edge of the tracer mass is the one that should be studied (Roels, 1984). Similarly, if fluorometers are being used (in dye experiments), the peak concentration or the first detected concentrations can be used.

By considering the velocity of the leading edge, the mean velocity will most likely be overestimated, when compared to cases when the center of mass movement is considered. In an attempt to improve accuracy and minimize the ambiguity and overestimation in mean velocity determination through dye tracer methods, Abrahams et al. (1986) proposed a method for obtaining the mean velocity of a stream, considering the variation of the velocity along the width of the stream. Based on current meters subsections averaged velocity Abrahams proposed a division of the stream in subsections and an independent determination of the leading edge velocity for each subsection. The global mean velocity would finally be computed from an average of all the velocities.

In the present thesis, an adaptation of Abrahams' method (Abrahams et al., 1986) will be used. The leading heated water front will be divided in three subsections and the mean velocity of the leading edge in each one of them will be computed. The mean velocity of the whole hot water front will then be obtained by computing the average of the three values.

For wider flumes and therefore wider study zone, more subsections can be chosen, in order to increase accuracy. For the present experimental setup, it was considered that three subsections were enough to properly represent the advance of the front.

The experiments resulted in footages in a compressed *".avi"* file format. This was a limitation because some programs are only compatible with the un-compressed *".avi"* file (e.g. imageJ). After several tryouts of multiple video and image editing software, the choice fell on *Adobe's Premiere Pro CS5.5* for applying some effects to the video, in order to accentuate and improve the visualization of the heat tracer, and then onto Kinovea, an open source video player, that stepped up as the most agile and easy to use tool for the quantitative analysis of the files.

Adobe Premiere CS5.5 is a powerful professional video editing software that allows users to work directly on the timeline (timeline based). It facilitates the mixing of different videos and features a big collection of effects. It was used for subtracting background, adding effects such as contrast, brightness, color substitution, color control, with the objective of enhancing visualization. Depending on the water heating method, there were cases where this image treatment could be skipped, because the hot water was already clearly visible. There were also cases where, even after these steps, it was impossible to properly visualize the videos. A similar approach was made by Chung & Grigoropoulos (2003) and Narayanan et al. (2003) where the radiative image of the background was subtracted from the full image with the heated flow, isolating the tracer. Then, the noise was smoothed using a Gaussian low pass filter effect. The results of this procedure can be seen in Figure 4.9.

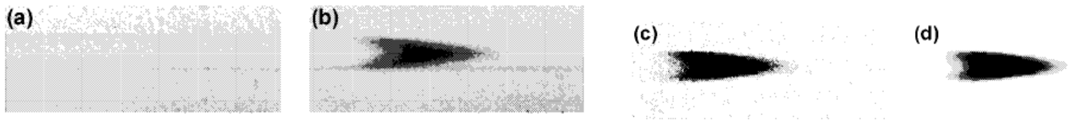

Figure 4.9 - Example of a similar image processing procedure: a) background image; b) captured heated water c) image with subtracted background; d) final image with *Gauss Low Pass* effect (adapted from Chung & Grigoropoulos, 2003).

Kinovea is an open source software, developed for sport videos analysis. It’s a video manipulation tool that allows measurement of distances and angles, point marking, side by side video comparison, tracking of objects, zoom and other useful features. This program was used to analyze the footage. It allowed the introduction of a grid and provided other useful tools like lines, and measurement tools, that facilitated the division of the heated mass in subsections (Figure 4.10).

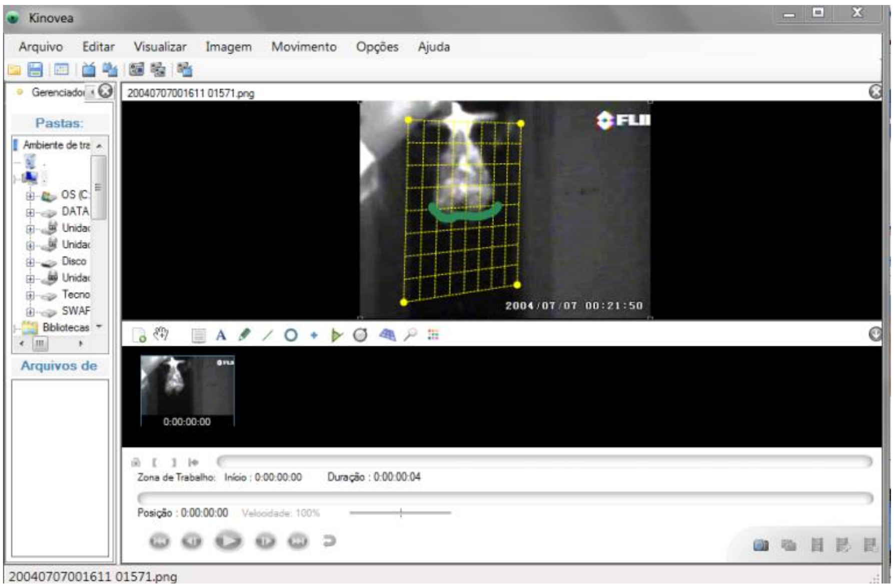

Figure 4.10 - Kinovea software screenshot with the grid and a drawn hot water mass front.

As an alternative, if video editing software is not available, the frames could easily be extracted from the video file (e.g. “Free Video to JPG Converter”) and analyzed frame by frame, as a succession of images. Although the extracted frames are easily identified by the time stamp in the image, this only provides information to the second, meaning that the frames had to be counted, and the time between frames must be known and used to compute velocity. Some early experiments were analyzed using this procedure.

The procedure for the acquisition of data for velocity computations is represented in Figure 4.11. The images were analyzed by defining two sections (yellow lines) separated by a variable distance (20 cm in this example). Similarly to the floats' method (section 2.5.8, Figure 2.7) the time that the leading edge takes to travel between both sections was measured (t_2-t_1). This was registered for three different subsections (left, center, right), whose central lines are represented in Figure 4.11 by three vertical lines. Finally, the velocity is computed by dividing the travel distance by the time interval, the mean velocity from the three subsections is calculated and the correction factor is applied (section 2.5.9).

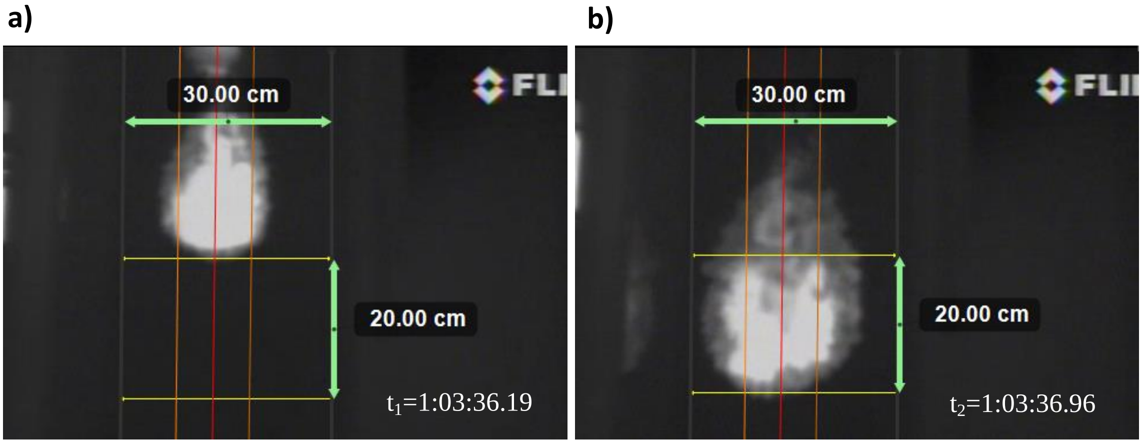

Figure 4.11 - Image interpretation procedure using Kinovea software.

4.4. Heat Generation

An ideal water heating method would be able to heat the water to a temperature easily detected by the camera, while causing low flow disturbance. It should also be easily accessible (low cost), versatile and portable for eventual field uses. In order to enhance velocity profile visualization, it should be able to homogeneously heat the full width of the stream. This would allow tracking the downstream motion and evolution of a straight line and provide valuable information about the velocity profile.

Similar experiments were already made for the flow of air and gases (Narayanan et al., 2003). However, due to the heat capacity of water (4.1813 J g^{-1} ºC^{-1}, at 25 ºC) being approximately 4 times larger than air's (1.0035 J g^{-1} ºC^{-1}, at 0 ºC), considerably more energy is needed to heat the water, especially when compared to the amount of energy needed for the same experiment for air flow visualization (Matsumura & Antonia, 2006).

Therefore, different methods were tested with the equipment available in the laboratory, in order to find the most suitable and effective option, which are described in the next sub-sections.

4.4.1. Hot Water Addition

Most experiments were conducted by adding water heated by an electric kettle into the flow. This, however, has unwanted implications. On the one hand, it is not easy to homogeneously add water through the width of the flume. On the other hand, the water dumping may cause unwanted disturbance in the flow such as waves or even significantly change the discharge value (depending on the amount of water added). Thus, a tradeoff has to be made in order not to add too much water that would change the flow, and to add enough water to ensure it is detected by the IR camera.

It was observed that the technique of adding water to the flow strongly influenced the quality of the visualization. It was noted that by dropping the water, it would sink and consequently complicate its detection by the thermographic camera. Alternatively, if the container was simply turned into the horizontal position, letting the water flow out by itself, the hot water would remain on the surface (hot water is less dense), enhancing visualization. Figure 4.12 illustrates this situation by showing the first case on the left, and the second on the right.

Experiments were made with a coffee cup, designed for retaining heat (material with low thermal conductivity). However, it was observed that the pouring technique was the most determinant factor for the success of the technique.

A wider recipient was also used in an attempt to release the hot water uniformly along the full width. However this wasn't very successful because it was more difficult to control the pouring and it introduced considerably more disturbance into the flow, when compared to a single cup.

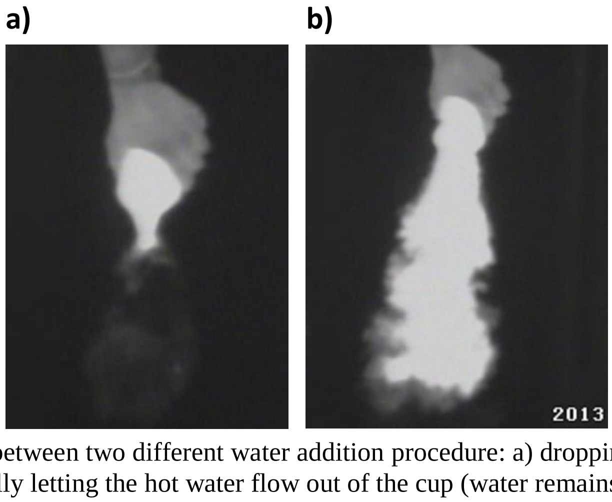

Figure 4.12 - Comparison between two different water addition procedure: a) dropping hot water that imediately sinks; b) carefully letting the hot water flow out of the cup (water remains at the surface).

From all the tested water heating methods, pouring water using a single cup was the one used more extensively, mostly because it provided the best way to clearly see the leading front of hot water. A comparison between the results of different quantities of added water (87.5 ml, 175 ml and 350 ml) will be presented in the Results section.

4.4.2. Heated Metal Slab

In this method, a gas torch was used to heat the edge of a thin metal slab (Figure 4.13). The edge of the slab is then submerged and its heat is transferred to the flowing water. It is observed that the slab cools fast when in contact with the water.

The slab has either been placed vertically with the largest side parallel or perpendicular to the flow. When placed perpendicularly, it originated considerably more disturbance in the flow, as it's easily explained by the size of the obstruction introduced. It's visible the formation of turbulent flow structures from the sides of the slab and its motion and evolution downstream. This method can be useful for visualization of turbulent structures; Liang & Chong (2011) already used a thermographic camera to study these processes by injecting hot water behind a cylinder. However, it might be interesting to use a heated piece of metal instead.

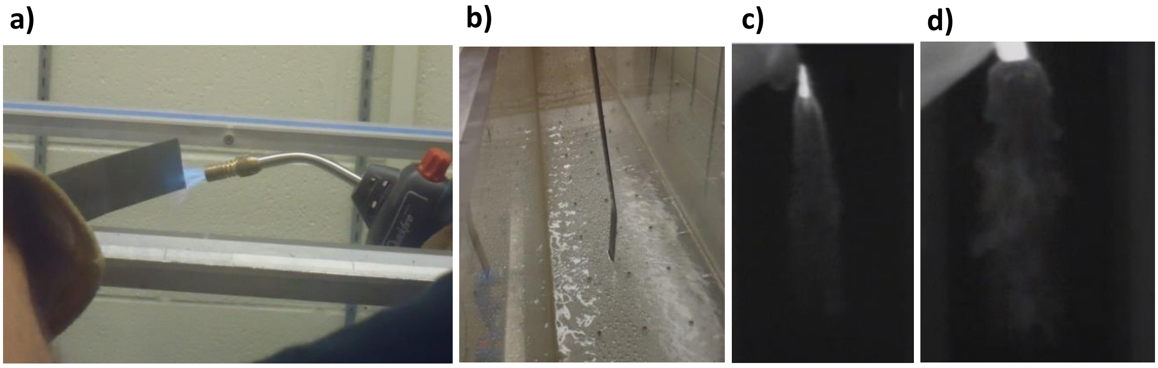

Figure 4.13 – Experiments using a heated metal lab: a) torch heating the slab; b) metal slab placed parallelly to the flow; c) IR image of experiments with the metal slab placed parallelly to the flow; d) IR image of experiments with the metal slab placed perpendicularly to the flow.

4.4.3. Heat Gun

Exploratory experiments were also conducted using a heat gun pointing at the flow. However, this method produced a strong stream of hot air that considerably disturbed the existing flow, compromising the results. Nevertheless, by approximating the heat gun to the flow, the resulting thermal images revealed a circular mass of heated water flowing downstream (Figure 4.14).

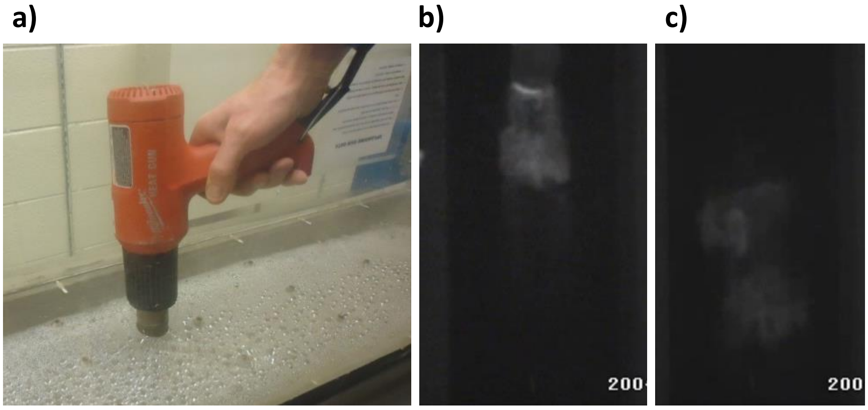

Figure 4.14 - Experiments using a Heat gun: a) Heatgun pointing at the flow; b) IR image few tenths of second after heating the water; c) heated mass from b) further downstream.

4.4.4. Heated Electrical Wire

The last attempt was to use a wire heated by an electrical current to heat the flowing water (Figure 4.15). The wood structure was adapted to fit inside the flume. A battery charger established an electrical current onto the wire. The current was pulsed, originating cycles of 6 seconds on followed by 6 seconds off.

However, the heated water was barely visible (Figure 4.15c). Even after editing the images for background removal or applying contrast, gamma, and brightness adjustments, it was impossible to infer about velocity. Clearly, the wire didn't heat the water enough, meaning that a more powerful device is needed. This method was not further explored in this work, but the expectation is that this method would allow to homogeneously heat the flowing water along the width of the flume, thus providing a lot of useful information.

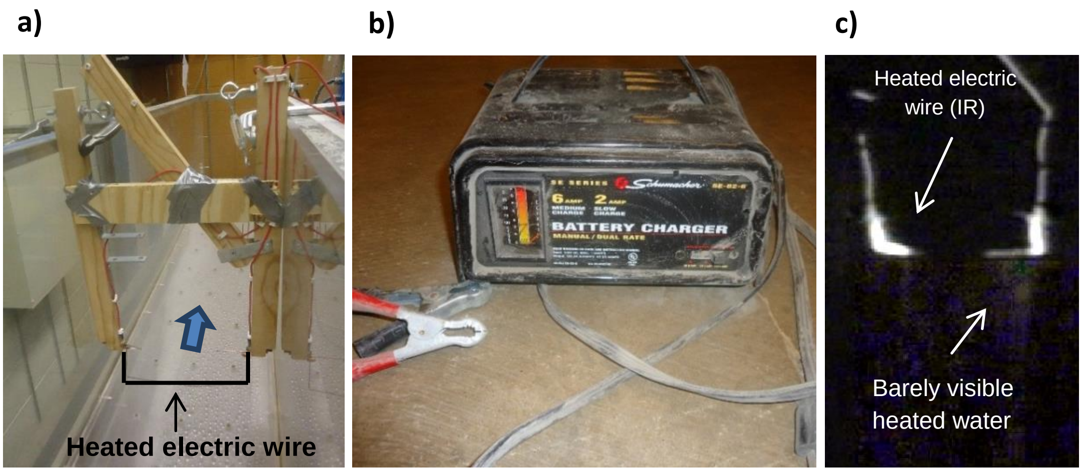

Figure 4.15 - Experiments using electrical current to heat the flow: a) structure adapted and placed into the flume; b) an electric wire was connected to a pulsed battery charger; c) IR image of the heated electric wire and its effect in the flowing water.

5. RESULTS AND DISCUSSION

5.1. Initial Considerations

In this chapter the results from the experiments are presented and discussed. It is divided in four different sections. In the first one, proofs of principle experiments are carried out for different flow depths and slopes. Then, the sensibility and response of the technique to variations in the water heating process and in the image interpretation process are analyzed. Finally, some other aspects and experiments are discussed.

The used experimental setup allowed: *i*) varying the flow conditions, namely the discharge/velocity (by adjusting the valve opening); *ii*) water depth (by adjusting the flume tailgate) and *iii*) slope. Concerning the water heating method, different methods (recipient hot water addition, metal slab, heat gun), quantities of heated water and upstream heating locations were tested.

During the experiments, the fluid (water), section geometry and roughness (flume) remained unchanged. On the contrary, the quantity of water in the hydraulic system might vary (hot water added from the tap, despite being balanced by leaks in the flume), temperature of flowing water in the circuit might increase slightly after a set of experiments (heat from pumps and hot water added to the recirculation circuit). Also, the hot water was heated once for each set of experiments, meaning that temperature may decrease in time due to heat losses. This was more significant and observable for the metal slab experiments which had to be heated again after four or five runs.

The presented results are mean values of sets of at least 6 runs (from 6 to 9). It is observed that the flow velocity standard deviation values are relatively low, fluctuating between 0.41 and 1.84 cm/s for velocities between 8 cm/s and 20 cm/s.

5.2. Proof of Principle

Figure 5.1 shows a compilation of all the average velocities of the sets of experiments and its corresponding standard deviations, compared to the values obtained using an ADV. It can be observed that most values obtained by this technique are overestimated when compared to the reference values from the ADV. This can be explained by the influence of the heating water method and the ADV location. The linear fit also revealed a tendency: the overestimation increases for lower flow velocities, what can be explained by the influence of the water heating method as will be analyzed in the following sections.

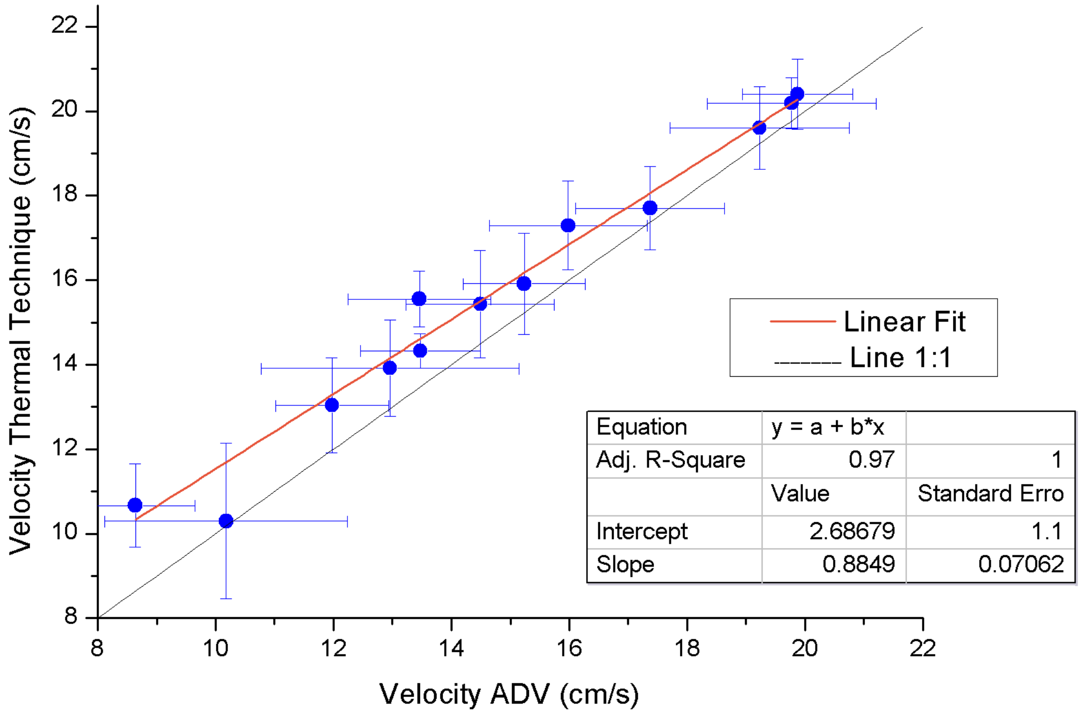

Figure 5.1 - Comparison between the velocities obtained using the thermal technique and the values obtained using an ADV, for different flow velocities, depths and slopes.

Different water depths and slopes were tested in different experiments. Figure 5.2 show a comparison between the obtained values with this heat tracer technique and an ADV reference velocity, this time identifying flow depths and slopes respectively. The technique performed well for the multiple tested conditions. Therefore, results show that the technique can be used for measurements in a wide range of water depths. Because hot water is less dense than colder water, as long as the hot water is properly poured into the flow surface or heated by a slab, it will remain in this top layer, thus allowing thermal visualization. Similarly to the dye tracing technique, the mean velocity can then be computed by multiplying the obtained surface velocity by the correction factor α, as described before in section 2.5.9.

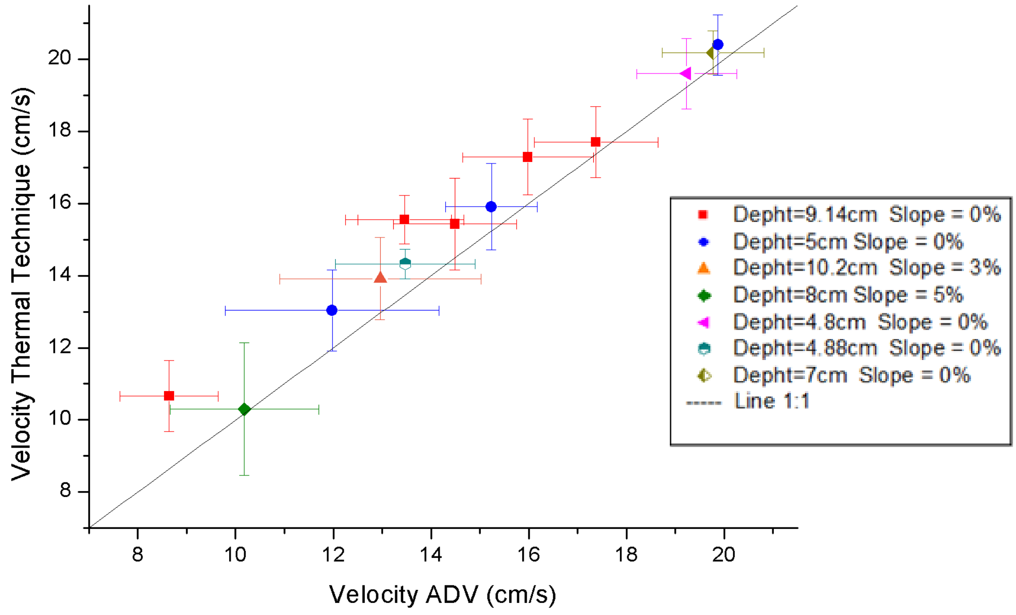

Figure 5.2 – Identification of slopes and depths used in the experiments (based in the graph of Figure 5.1, comparing velocities from the thermal technique to ADV velocities).

5.2.1. Technique's Velocity Range.

The detectable velocity range for this technique is limited on an upper level by the camera frame rate. For the installation used in this thesis (IR camera hanged 1.5 m above the flume), a display length of 55 cm was provided (maximum useful travel length of 40 cm assumed). Table 5.1 shows a correspondence between different flow velocities and the number of frames captured by the camera (with the hot water mass inside the recorded zone). It can be concluded that this frame rate allows the detection of high velocity flows, providing at least two frames for velocities up to 500 cm/s (not tested in the present work).

Regarding the applicability of the methodology for lower velocities, the limitation concerns the water heating methods, with results becoming more or less overestimated, depending on the method used and on the disturbances it induces to the flow, as it will be analyzed below.

Table 5.1 - Correspondence between flow velocity and number of frames available of the thermographic images.

	Travel length of 40 cm		Travel length of 20 cm	
Velocity (cm/s)	Travel Time (s)	Nº Frames	Travel Time (s)	Nº of frames
5	8	240	4	120
10	4	120	2	60
20	2	60	1	30
50	0.8	24	0.4	12
100	0.4	12	0.2	6
250	0.2	6	0.1	3
500	0.08	2.4	0.04	1.2

5.2.2. Effect of Channel Slope

When experiments are performed with slopes other than 0%, the flow plane no longer corresponds to the projection captured by the camera, thus the measured distances in the recorded images do not correspond to the real distances. To account for this effect, the measured distances have to be increased, resulting in an increase of the velocity (water takes the same time to travel a bigger distance). However, this effect has a minimal effect in the velocities since it only starts being significant for slopes over 8% and velocities over 30 cm/s (assuming a travel distance of 15 cm). For these conditions (experiments performed for the present thesis are below these values), the velocity increase will be of 0.1 cm/s which is considerably smaller than the standard deviation values obtained in the experiments. Nevertheless, this was accounted for in the velocity computations from the experiments. A solution for this problem would be simply rotating the thermographic camera to match the channel slope. However this was not done, thus the correction was applied.

5.3. Water Heating Variables

5.3.1. Different Quantities of Added Water

In order to study the effect of the quantity of added water variations in the final velocity results, experiments were made using three different quantities (Figure 5.4), for three different velocities. From the analysis of Figure 5.3 it is possible to conclude that the method is more sensible to these variations when dealing with lower velocities. In addition, higher quantities of added water increase the overestimation of flow velocities. These conclusions are in accordance with the expectations because this method is invasive and the conditions of the flow (discharge and velocity) can be altered, of course, depending on the amount of water added. This effect being more significant for slower velocities is also logical as it is easier to disturb such velocities. Also, the water pouring movement itself might have some influence on this, because it's impossible to lay the water without an initial velocity and without causing any disturbances to the flow.

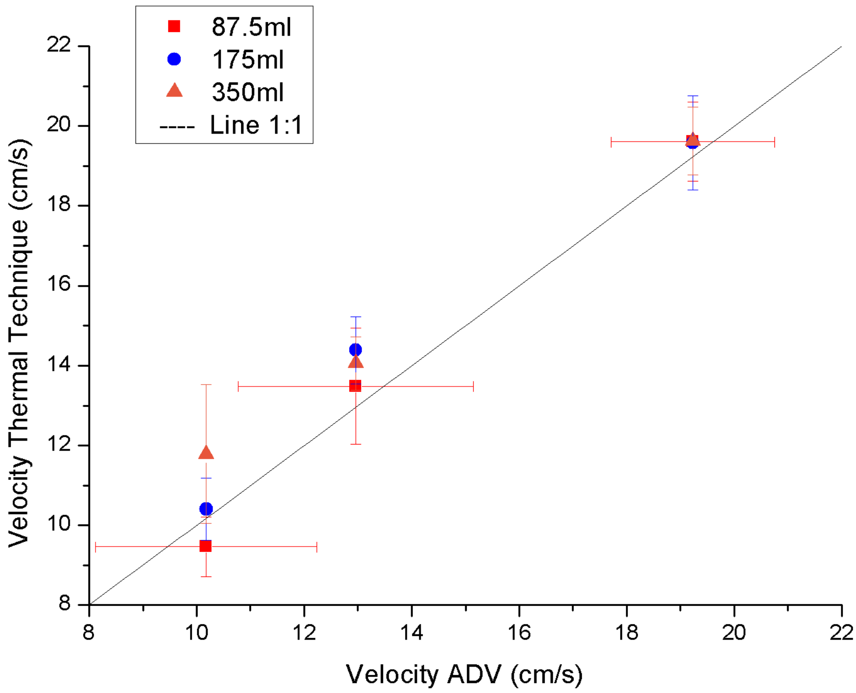

Figure 5.3 - Comparison between velocities obtained with the thermal tracer technique and the ADV, showing the influence of the volume of hot water added to the flow.

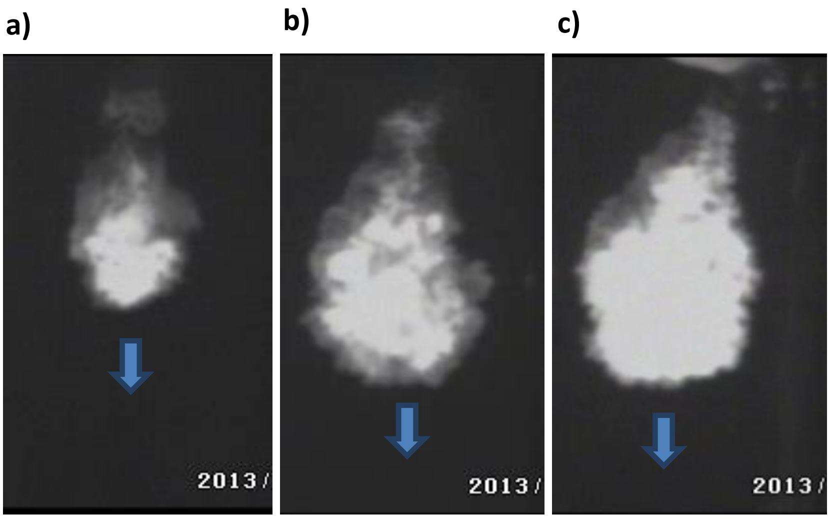

Figure 5.4 - Different quantities of added hot water visible through infrared thermography: a) 87.5 ml; b) 175 ml; c) 350 ml.

For the following experiments, the medium quantity of water was used (175 ml). This quantity provides enough water to ensure proper visualization. Smaller quantities of water fade faster, loosing intensity and are more influenced by the turbulence originated by the introduction of the hot water into the flow. Bigger quantities of water may complicate the analysis because it can easily originate multiple masses of water that overlap each other, and there isn't any clear advantage on using more water.

5.3.2. Wider Container

As an attempt to introduce water through the full width of the channel, a wider recipient was used. However, similarly to what was mentioned before, dropping water from above caused the water to sink and thereby hindered its visualization. Therefore, in order to properly spill the water into the flow it was necessary to touch the water with the container, so it could flow out. This procedure, with this wider recipient, inevitably originates a considerable barrier on the top layer of the flow, which obstructed the flow, causing significant surface disturbances. In addition, it was complicated to homogeneously release the water through the container edge. For these reasons, this attempt did not provide analyzable results and was abandoned in this laboratory experiments.

5.3.3. Distance from Hot Water Addition Point

In most experiments, water was added to the flow near the upstream edge of the recorded area. However, experiments were also made adding hot water at different distances upstream. Figure 5.5 shows that the overestimation described above related to water introduction decreases as the water is introduced further upstream from the recorded area (in Figure 5.5 data points are below the 1:1 line). Standard deviation parameters also follow the same tendency. Regarding the variation with velocity, no obvious conclusion can be drawn from results. These conclusions can be explained by considering that the disturbance effect originated when adding the water has enough time to get dissipated, and that the hot water has more time to fully acquire the real flow velocity, thus presenting more accurate results.

This procedure also allowed perceiving that the hot water behavior highly depends on flow velocity. For faster flows, the hot water mass strictly followed the current lines, showing an elongated shape with minimal lateral mixing. For slower flows, the hot water spreads along the full width and is more sensitive to disturbances in the flow.

Another important outcome was that, in both cases, it was still possible to clearly identify the hot water mass added at the upper end of the flume (3 m upstream), contradicting the expectation that the hot water would rapidly mix with the colder water from the stream, becoming barely visible after travelling a significant distance. This naturally varies with the quantity of water added to the flow, its temperature, turbulence and sensibility for temperature variations of the thermographic camera.

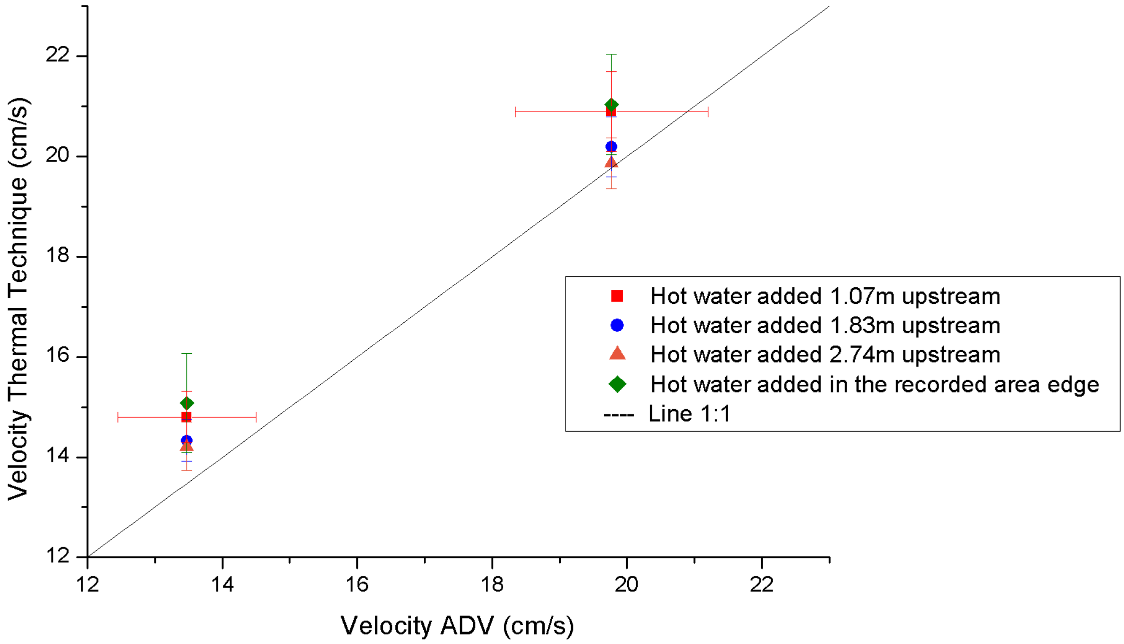

Figure 5.5 - Comparison of the results from the thermal technique by adding the water from different distances upstream from the recorded area with the reference velocities obtained using the ADV.

5.3.4. Heated Metal Slab Experiments

Figure 5.6 shows a comparison between the velocity values obtained using a metal slab to heat the water and by adding water to the flow (medium quantity – 175 ml), for three different velocities. Results obtained using a slab are systematically lower than the others. They also presented lower variability, with standard deviation values fluctuating between 0.52 and 0.66 cm/s, in opposition to the standard deviation values from experiments with the addition of water that originated sets with standard deviations over 1 cm/s. The increase of overestimation for lower velocities in the hot water addition experiments was again confirmed. In opposition, this same tendency wasn´t observed in the experiments using the slab. These results suggest that the use of the slab to heat the water causes less disturbances to the flow and is more constant. 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.

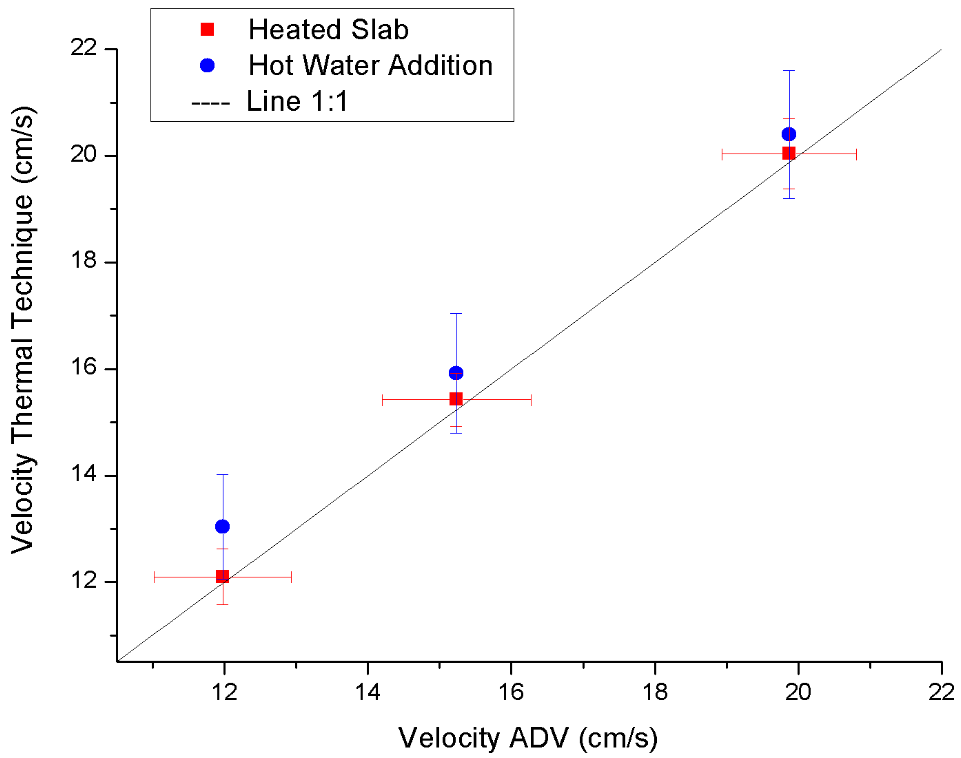

Figure 5.6 - Comparison between the velocities from the thermal technique and using an ADV, for two different water heating methods (heated metal slab and hot water addition).

5.4. Image Interpretation Variables

Image interpretation is an important phase for the success of this technique. The fact of having recorded images that enable rewind and forward video capabilities, along with a 30 frames per second rate, contribute to the good degree of precision that can be achieved in this phase. However, this task still requires a considerable amount of human judgment that can have significant influence in the final results.

5.4.1. Comparison of Velocities in Different Subsections

Each run of experiments was analyzed by dividing the hot water mass in 3 subsections (left, right, center), computing the velocity in each one, and finally calculating an average of the three to obtain the mean surface velocity. However, the results of this procedure didn't always match the expected outcomes. Figure 5.7a shows that the velocity from lateral subsections were sometimes higher than the central ones, revealing that spreading of the hot water when introduced into the flow had influence in these velocities. In addition, in most cases the front wasn't symmetric, suggesting heterogeneity in the water pouring movement (hand tilting the cup).

In the experiments using the metal slab, it was observed that, in most cases, center point velocity was lower than the one from the sides (Figure 5.7b). This actually makes sense because the metal slab introduces an obstacle into the stream, forcing the water to split to the sides, creating a turbulent structure that has its converging point behind the metal slab, which is aligned with the center of the stream. In addition, results for the slab method were also more consistent than the ones that involved adding water to the flow.

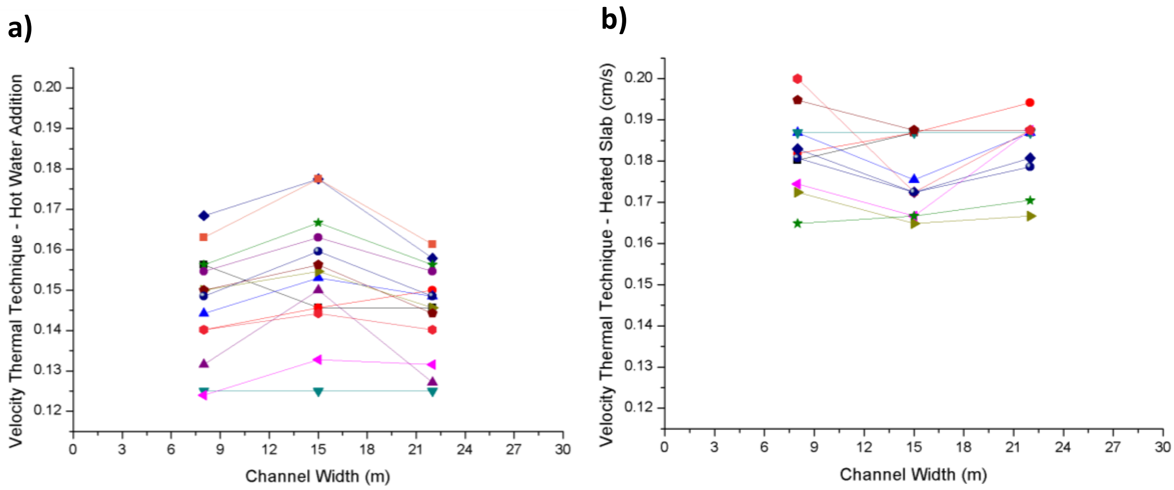

Figure 5.7 - Velocities in the different water front subsections (different runs from each set of experiments, values not multiplied by the correction factor α) for: a) hot water addition; b) metal slab.

5.4.2. Leading and Intense Hot Water Fronts

During the experiments where hot water was added to the flow, 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 image Figure 5.8. Therefore, two distinct velocities can be obtained, one considering the fastest leading front and other considering the most intense front. This aureole is most likely caused by heat losses from the water in the edge of the hot water mass, when in contact with the colder water from the stream. However, it can also be explained by overestimation considerations, assuming that the aureole is caused by heat transfer from the hot water mass to the surrounding water. This aureole was more pronounced when working with lower velocities.

Results from this thesis were obtained considering the leading front. However, both velocities were considered for a set of experiments in order to analyze the influence of this option on velocity measurements.

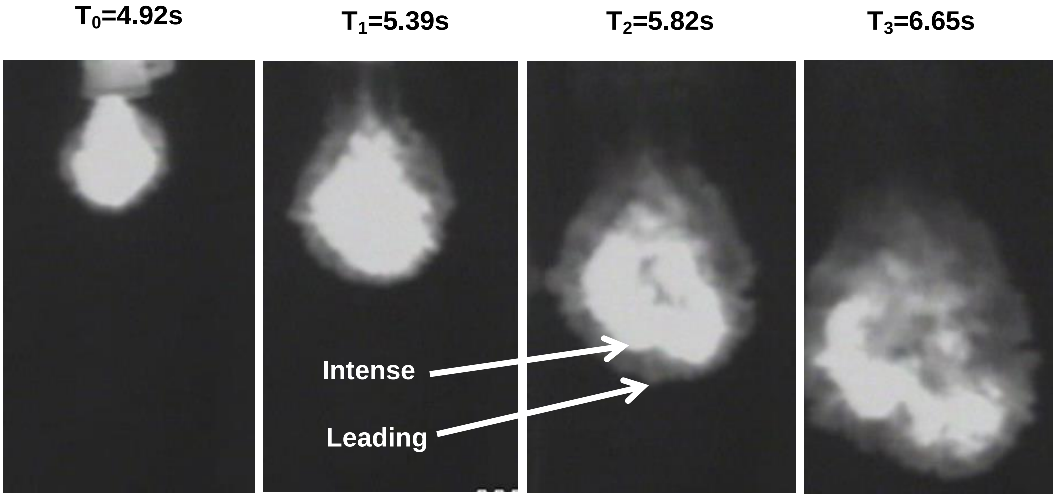

Figure 5.8 - Illustration of the leading and intense hot water front and its movement downstream.

Figure 5.10 represents the evolution of the velocity of both fronts. The recorded area was divided in three regions of 0.15 m and the velocity in each one of them was measured and then represented in the graph. It is observable that the leading front velocity is always higher than the intense front.

From previous sets of experiments (computed using a 0.2 m region as explained in section 4.3), the estimated flow velocity is similar to the one computed for the last region. The tendencies shown in Figure 5.10 for different velocities, can be explained by considering that the velocity in the first region is highly influenced by the initial velocity induced by the water spilling, and then as the distance to the point of water addition increases, it starts converging to the real flow velocity. According to the values from Figure 5.10, this initial velocity is likely to be around 15 cm/s. In order to confirm this value, the time of the water addition process was estimated from the recorded images (average of 0.88 seconds) which, when related with the amount of water added (175 ml), allowed the determination of the discharge from the cup (199 cm^3/s). For the cup (8 cm diameter) and water height (2.5 cm, observed during experiments) represented in Figure 5.9, the water is placed into the flow with an initial velocity of ~15 cm/s (Equation 5.1).

$$Q = \frac{175cm^3}{0.88\ s} = 199\ \mathrm{cm^3s^{-1}} = \mathrm{U} \times \mathrm{A} \Leftrightarrow U = \frac{199\ \mathrm{cm^3s^{-1}}}{13.42\ \mathrm{cm^2}} = 14.82\mathrm{cm^3s^{-1}} \tag{5.1}$$

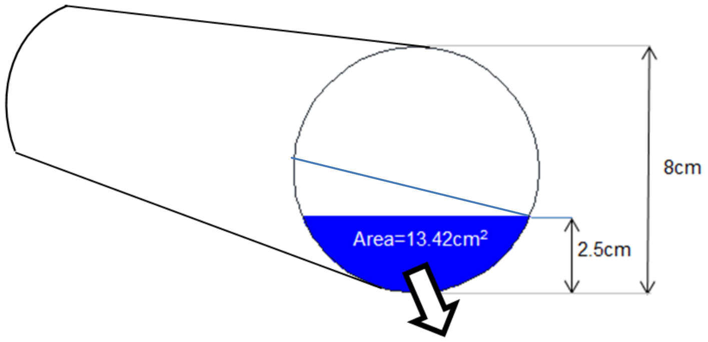

Figure 5.9 – Parameters for initial added hot water velocity estimation: cup diameter, estimated water height during pouring and cross sectional wetted area.

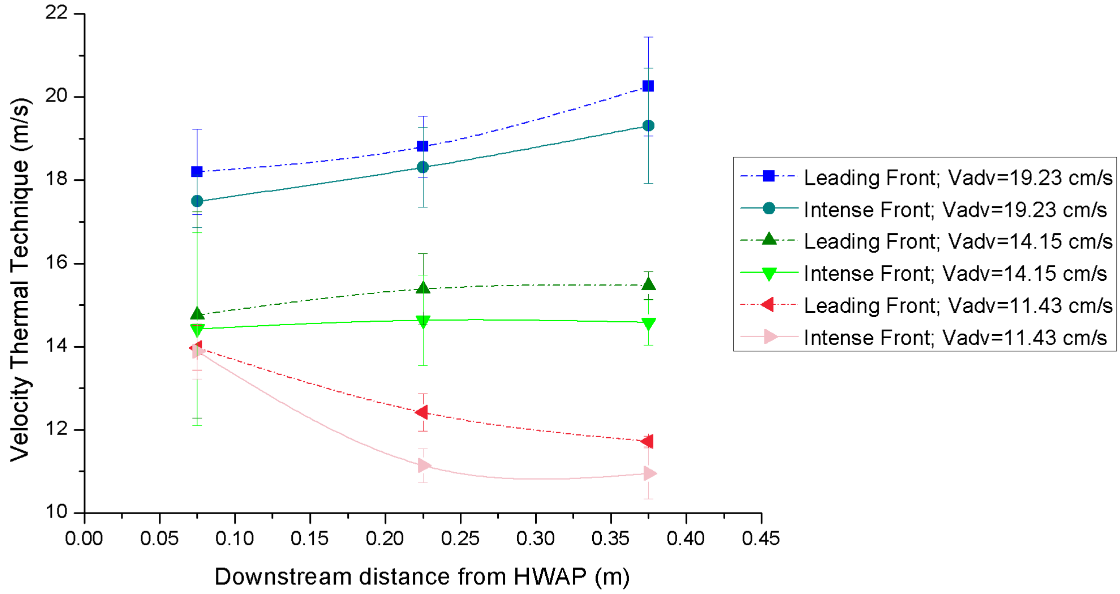

Figure 5.10 - Comparison between velocity of the leading and intense hot water fronts. Evolution of velocity in the recorded area (three downstream subsections of 0.15 cm), for three different flow velocities. HWAP means hot water addition point.

5.5. Additional Experiments

5.5.1. Effect of Vegetation

An attempt was made to study the performance of the technique when vegetation is present (some branches and leafs were attached to the flume bed). Despite the view being blocked by the taller vegetation, it was still possible to observe preferential paths. This had no applicability for velocity measurements, but it can be an important outcome for future experiments.

5.5.2. Turbulent Zones/Hydraulic Jump

In the presence of a turbulent zone, velocity information can hardly be obtained from the videos. The visualization of surface temperatures can, however, be relevant for other purposes, namely for the study of turbulent structures or the analysis of preferential paths within the turbulence. With the available flume, it was easy to create a hydraulic jump, whose presence was easily identified in the videos because the added hot water immediately sinks and disappears from the footages, upon arrival to this zone (Figure 5.11).

Figure 5.11 - Hydraulic jump viewed by thermography.

6. CONCLUSIONS

Nowadays, a huge set of options for flow measurement techniques are available, based on the most various principles, and for a wide price range. Despite the existence of powerful and widely used measurement techniques, there is still space for innovative new techniques to emerge, especially if they provide new solutions, at an affordable price, for measurements under certain unfavorable conditions, for which the use of conventional techniques is usually limited (e.g. shallow flows).

Similarly, in flow visualization techniques, there are already methods that guarantee quality in the observation of various processes and that inclusively allow reliable quantification. Nevertheless, with the sophistication of new imaging techniques, progress in research is expected to continue at a high rate in the next years with the development of more effective and accurate methods (numerical or experimental) and the improvement of emerging visualization techniques (e.g. PIV, BIV) in order to improve spatial and temporal quantification of the flow. Research on shallow flows is also focusing on determining the extent to which scale effects influence measuring and flow visualization methods.

Within this framework, a technique was outlined and some exploratory experiments were performed. The most significant conclusions from the experimental work are listed below:

- Results were in accordance with the velocities obtained using an ADV, however always slightly overestimated.
- The technique performed well for multiple slope and depth conditions, under the experimented settings used.
- From the tested water heating methods, the heated metal slab and the hot water addition were the only that could provide analyzable data. The use of the heat gun significantly disturbed the flow, compromising results, while the hot wire didn’t have adequate power to heat the water enough, thus it was not possible to identify and track a hot water front in the flow.
- It’s preferable to add hot water further upstream from the recorded area in order to allow time for the hot water to acquire the flow velocity.
- The quantity of added water had influence on the results, with higher quantities contributing to an overestimation of velocity.
- Adding water manually originated variability in the results, with relatively high standard deviation values, that increased the uncertainty of the measurements.
- Experiments using a metal slab consistently revealed lower standard deviation values, and provided less overestimated values of velocity.

- The presence of strong turbulence, hydraulic jumps and other situations where the surface is significantly disturbed jeopardizes velocity measurement results. It however revealed potential of the technique for flow visualization purposes, as turbulent structures (e.g. wakes, eddies, vortices) and mixing processes are visible.
- The analysis of three different subsections of the hot water front showed that while in the hot water addition experiments the central velocity was usually higher than the ones from the sides, for the metal slab experiments it was lower (water forced to contour the slab).
- Experiments revealed the existence of a well-defined lighter aureole around a more intense hot water mass. The leading front always presented slightly higher velocities than the more intense front.

The main advantage of the technique relies in the fact that the used tracer is also water, thus its shares most of the properties of the initial water in the flow, what is crucial for the success of a tracer. Density is however known to vary with temperature, but it can actually be an advantage because it contributes for hot water to remain at the surface where it can be visualized through thermography. In opposition to dyes or electrolyte tracers, no chemicals are added to the flow, avoiding problems with environmental concerns. Heat can eventually have some negative impact on habitats, but for local single measurements it is hardly problematic. In addition, the tendency for the formation of conglomerates on the water surface due to surface tension effects is avoided. The portability of thermographic cameras is also an advantage as it opens good prospects for uses in the field. Because the method involves recordings and posterior image processing, results are not dependent on human reaction, which reduces uncertainty.

This technique can be useful especially when dealing with shallow water depths that are inherently complicated to measure, often colliding with minimum working depths of equipment (e.g. mechanical current meters), or affected by the inevitable interference of boundary conditions (e.g. reflection of waves of ADCPs). Also, the technique has no constraints regarding the use in the presence of sediments, debris or rock, which is usually a limitation for other methods because it may cause damage to the instruments. In cases where the flow is inaccessible, this method might still be used, by placing the camera obliquely to the flow (in an accessible zone nearby) and by considering a distortion to the images.

The presented technique is still at an early stage and used inexpensive technology. With the development of the present work, it was recognized that it is possible to improve the accuracy of results. The most noticeable aspect was the added value and research options that would be available if a more advanced thermographic camera with higher capacities was used, since it would provide temperature quantification and higher spatial resolution. Also the tested water heating methods are still far from the ideal solution for this technique, because lower surface disturbance, less intrusion into the flow and less variability between experiments are key points.

Future Work

The technology revealed potential not only for velocity estimation purposes but also for distinct approaches. Some proposals and ideas for future studies are listed below:

- Application at a larger scale. The use of a wider flume would enhance the simulation of shallow and overland flows, and allow the study of two dimensional processes.
- Development of more efficient methods to locally heat the water (e.g. more powerful hot-wire device; heat tape; infrared laser beams).
- Use of a research oriented thermographic camera of higher resolution would open new prospects and options (e.g. analysis similar to PCA (section 3.2.7), study and modeling of heat dispersion processes, study of turbulent mixing characteristics, assessment of cooling water releases).
- Automatization of procedures, namely the use of a strobe water heating method, would eventually allow the continuous measurement of velocity. The image interpretation phase can inclusively be programmed in order to make more agile the process of obtaining velocity from the video footages.
- Feasibility as a flow visualization method for preferential paths analysis, namely to visualize curve trajectories, movement of the water around obstacles, influence of vegetation (e.g. wetlands). Visualization and quantification of turbulent structures (e.g. wakes, vortices, eddies)
- Analysis of the applicability of the technique for uses in the field: influence of wind and rain (wind increases surface heat loss though the surface while rain is likely to compromise visualization).
- Modeling of the wave originated by the addition of hot water to the flow, and study of its influence in flow velocity.

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