Measurement 45 (2012) 1015–1022

Contents lists available at SciVerse ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Thermal imaging study of temperature fields in shallow flows

Dongfang Liang *, Jack Mao Chen [1], Kelvin J.Y. Chong [2], Camilla McCorkell

Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK

A R T I C L E I N F O

Article history:
Received 21 March 2011
Received in revised form 30 October 2011
Accepted 31 January 2012
Available online 10 February 2012

Keywords:
Environmental hydraulics
Shallow flow
Turbulent mixing
Thermal imaging

A B S T R A C T

Thermography has been used to investigate the scalar transport in shallow-water jet and wake flows. Warm water was injected uniformly over the depth into these flows, and the temperature variations at the water surface were captured by a thermal camera. The mixing of the warm water with the ambient fluid in shallow flows, as the result of turbulent diffusion and dispersion, was analysed. The development of the mean and fluctuating temperature along the flow was examined and compared with the past studies of scalar transport in shallow jets and wakes. The results agree well with the theoretical analyses and the previous measurements, where dye was used as the tracer. Through the detailed studies, it has been demonstrated that thermal imaging technique provides a new quantitative method for studying turbulent mixing phenomena in shallow waters. Compared with conventional scalar measurement techniques, the biggest merit of the thermal imaging method is that it involves a very simple experimental setup.

1. Introduction

Shallow water flows are bounded by the bed and free surface, and their horizontal dimensions are much larger than the water depth. Therefore, the flow is confined within a relatively thin layer. The flow in wide river channels, lakes, estuaries and coastal regions can all be classified as shallow [16]. The limited depth means that the development of vertical flow structure is restricted, so variation of the flow in the vertical direction is less important than that in the horizontal direction. This means that the overall analysis of the problem can be conducted in a depth-averaged manner. The large-scale quasi two-dimensional flow structure play an important role in the exchange of momentum, mass and heat in the flow.

Turbulent mixing is a key subject in environmental engineering. A better understanding of the scalar transport process in shallow waters is essential for minimising the adverse effects of wastewater disposal, oil leakage and chemical effluent on aquatic ecosystem. Balachandar et al. [1], Chen and Jirka [6], Balachandar et al. [2], Carmer et al. [5] and Jirka [10] are examples of studies dedicated to investigating the turbulent mixing process in the shallow jets and wakes. All these studies use dye concentration to indicate the scalar quantity. Since temperature is also a scalar quantity subject to the advection and diffusion in the flow, the temperature field should develop in a similar way to the concentration field.

In fluid mechanics, there are two types of quantitative measurement techniques: point-wise ones and full-field ones. Significant advancement made in the imaging technology has witnessed the development of various non-intrusive full-field scalar measurement systems, such as the Planar Concentration Analysis (PCA) and Laser Induced Fluorescence (LIF) methods. They obtain the simultaneous scalar field by measuring the dye concentrations. The PCA technique relies on the variation of the fluid colour with the dye concentration to quantify the scalar transport process. In numerous past studies with the PCA technique,

* Corresponding author. Tel.: +44 1223 764829; fax: +44 1223 332662.
E-mail addresses: d.liang@eng.cam.ac.uk (D. Liang), mc629@cam.ac.uk (J.M. Chen), caseyjy2002@yahoo.com (K.J.Y. Chong), camilla.mccorkell@cantab.net (C. McCorkell).
[1] Tel.: +44 1223 748580.
[2] Present address: Sime Darby, Kuala Lumpur, Malaysia. Tel.: +60 12 2880375.

0263-2241/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.measurement.2012.01.042

colorimeter is used to measure the concentration field from above the water surface, yielding effectively an integrated measurement over the depth. For the LIF technique, a laser beam is used to excite certain dissolved dye tracer, which emits fluorescent light at a different frequency and wavelength to the source laser beam and whose intensity is related to the concentration of the fluorescent material (e.g. [4]). The advantage of the LIF technique is that it acquires the local concentrations within the flow domain, where the laser passes through, rather than the depth-averaged concentrations.

This study explores the feasibility of using thermal imaging to investigate the scalar transport process in shallow flows. Although thermal imaging in itself is not a novel technology, the application of this technique to quantitative flow visualisation has been rare in laboratory studies. Traditionally, various types of point-wise thermometers are used to measure the fluid temperatures (e.g. [7,11]). By contrast, thermal imaging non-intrusively measures the temperature field. In this study, temperature difference in the water body is created by injecting warm water into the ambient water of room temperature. The entrainment of the warm water is monitored by an infrared camera. A key advantage of the thermal imaging method over other scalar measurement techniques, such as the LIF and PCA methods, is that it involves very simple experimental setup and requires little calibration. The present application of the thermal imaging technique assumes that the background flow isothermal. Bejan [3] shows that impressible turbulent jet flow is not actually isothermal. Even when the temperature difference between the nozzle fluid and the ambient fluid is zero, the jet region is non-isothermal because of the thermodynamic effect during entrainment and entropy generation. However, the Bejan [3] found that the maximum temperature rise is normally negligible, e.g. less than 0.15 °C. The isothermal assumption of the background flow is valid in this study, because the measured temperature differences are at least an order of magnitude larger than those due to the thermodynamic effect.

2. Thermal imaging technique

Thermal imaging is the conversion of electromagnetic waves emitted by a body into images. The thermal radiation as a result of an object's temperature is linked to the temperature of the object, T, and follows the Stefan–Boltzmann Law of radiation:

$$I = A\varepsilon\sigma T^4 \tag{1}$$

where I is the power radiated by an object of area A, ε is the emissivity of the object, σ is the Stefan–Boltzmann constant, and T is the absolute temperature. Water has an emissivity of around 0.98, indicating a thermal radiation behaviour similar to a black body. In the present experimental condition, atmospheric radiation and reflection from surrounding objects are insignificant, so they are neglected in the analysis. A thermal imager is able to measure the emitted energy by the object and convert it to a corresponding temperature. The temperature distribution is represented by the distribution of visible light – a picture. It should be pointed out that water is opaque to medium and long wave infrared, so only the temperature at the surface of water is detected by the thermal camera. For shallow flows, the variation of temperature over the depth is very small compared with its changes in horizontal directions, so it can be assumed that the vertical temperature distribution is homogenous. Thus, the surface temperature can be used to represent the temperature of the water column at one horizontal location.

According to Rainieri and Pagliarini [15], there has been an incredible advancement in thermal imaging technology, with the introduction of focal plane array sensors. However, with this innovation, non-uniformity of the photo sensor array becomes the largest impediment to the performance of any modern infrared camera. Non-uniformity errors are introduced when a highly diffused image is measured by a linear array photo sensor calibrated in a specular mode, manifesting themselves as unexpected streaklines in the captured image. A Land Guide M4 infrared camera, which has a frame rate of 25 Hz and a resolution of 19,200 pixels (160×120 pixels), is used for quantitative flow visualisation in the present study. It performs a non-uniform calibration automatically by applying a correction factor to the matrix of sensor outputs. Non-uniformity errors are not an issue when the camera is used to capture still images, as a pixel-by-pixel calibration can be performed just before a picture is taken. When the camera operates in video mode, though, the camera initiates a self-calibration when a prescribed tolerance for non-uniformity error, e.g. ±2%, has been exceeded. An infrared camera having a smaller error tolerance will self-calibrate more frequently during the video recording, through which a high level of accuracy is achieved.

The Land Guide M4 infrared camera used in this study can measure temperatures between −20 °C and 250 °C at a sensitivity of 0.12 °C. Rather than using the camera's full range of the temperature variation, the temperature range in this study is narrowed down to 18–27 °C, giving a higher resolution of 0.035 °C. This range has been carefully chosen, so the maximum and minimum temperature values measured for all experiments falls within the prescribed range, and no pixel saturation occurs. In this study, still images are extracted from the video footages recorded by the camera at fixed time intervals using video processing software. The still thermal images are then converted into greyscale format, and the relationship between the temperature and the greyscale number can then be established. The calibration of the thermal camera is done by cooling boiling water and taking regular temperature measurements with a thermal couple and the camera. Fig. 1 demonstrates the linear relationship between greyscale numbers and measured temperatures.

3. Experimental setup and procedure

Experiments in the present study are conducted in a versatile hydraulic flume, which is 2.1 m long and 0.6 m wide. A sketch of the experimental apparatus is illustrated in Fig. 2, together with the definition of coordinates and some parameters. The flume bed and sidewalls are well