

Penetrative convection in stratified fluids: velocity measurements by image analysis techniques

by

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ABSTRACT

The flux through the interface between a mixing layer and a stable layer plays a fundamental role in characterizing and forecasting the quality of water in stratified lakes and in the oceans, and the quality of air in the atmosphere. The evolution of the mixing layer in a stably stratified fluid body is simulated in laboratory when “Penetrative Convection” (CP) occurs. The laboratory model consists in a tank filled with water and undergone to controlled and reproducible boundary conditions. Laser Induced Fluorescence (LIF) allows the mixing layer evolution to be visualized. Pollutant dispersion phenomena are naturally described in the Lagrangian approach as the pollutant acts as a tag of the fluid particles. To this aim, Particle Tracking Velocimetry (PTV) and Feature Tracking (FT) are used to reconstruct the velocity field through detection of tracer particle trajectories moving within the measurement volume.

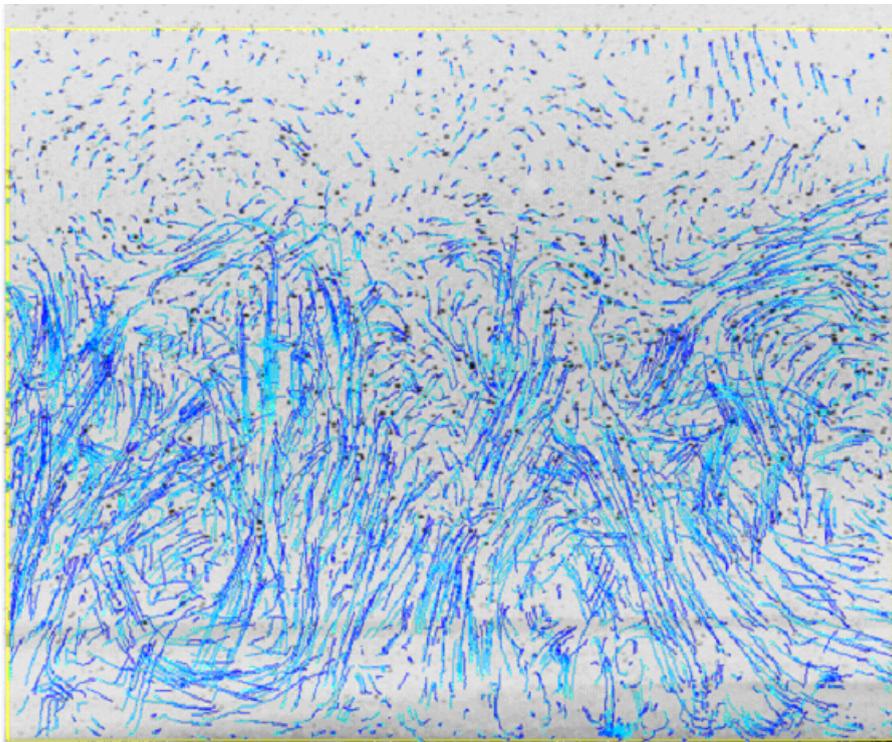


Fig. 1. Time evolution of features tracked through the technique Feature Tracking. The mixing layer is almost at the top of the test section. Internal waves are visible in the remaining stable layer

1. INTRODUCTION

Penetrative convection concerns the advance of a *turbulent* fluid into a fluid layer of stable stratification. The phenomenon is organized in domes, space regions with prevailing vertical motion. Domes springing up the heating surface stress the stable layer causing the generation of internal waves. These ubiquitous motions take many forms, and they must be invoked to explain phenomena ranging from temperature fluctuations in the deep ocean to the formation of clouds in the lee of a mountain. Within the unstable layer, the fluid temperature, density and velocity change with time. Further, it is separated from the rest of the fluid through an interface where large gradients of quantity of interest occur. The investigation of penetrative convection is of importance in several areas of geophysical fluid dynamics, since it occurs in the upper oceans, lower atmosphere and upper lakes. In this regard, we must recall that natural fluid bodies are characteristically stably stratified: that is, in most regions and for most of the time the average density decreases as one goes upwards.

The phenomenon interests the atmosphere when a *turbulent* convective fluid covers a large horizontal area, and gradually deepens and incorporates a stable fluid layer above it. This phenomenon is observed when, owing to surface heating, a growing unstable layer adjacent to the ground replaces from below a nocturnal inversion. In this case, the initially stable environment near the ground is affected by the convection, and full interaction between the two regions occurs. The convection is termed penetrative because the front of the advancing unstable layer presents domes that penetrate small distances into the stable layer (Deardorff *et al.*, 1969).

In most lakes and in the oceans, an analogous phenomenon occurs, starting from the upper, free surface and eroding with time the daily but mostly the seasonally stably stratified lake waters.

The present paper describes the application of PTV and FT to a laboratory model simulating the evolution of a convective boundary layer. The basic idea behind Particle Tracking Velocimetry is to disperse the seeding particles homogeneously in the working fluid and tracking them during their motion. On the other hand, Feature Tracking matches by selecting image features and tracking these from frame to frame. The matching measure used to follow a feature (and its interrogation window) and its “most similar” region at the successive time is the “Sum of Squared Differences” (SSD) among intensity values: the displacement is defined as the one that minimized the SSD. The description of the velocity field resulting from both techniques is intrinsically Lagrangian. Visualization experiments through LIF are presented as well in order to visualize the evolution and shape of the interface between the stable and unstable layers. Townsend (1964), Deardorff *et al.* (1969), Kato and Phillips (1969), Cenedese and Querzoli (1994), Querzoli (1996), Cenedese and Querzoli (1997) and Mancini and Cenedese (2000) present laboratory investigations on penetrative convection. A larger set of boundary conditions and the application of FT as well as of a refined PTV algorithm differentiate the present contribution.

2. EXPERIMENTAL SET-UP

The laboratory model consists of a convection chamber heated from below. The heating simulates the solar radiation effects and causes penetrative convection. The working fluid is distilled water. Pollen is used as passive tracer. The test section, shown in Figure 1, is a cylindrical tank of 41×41 cm² square cross-section and 40 cm of height. 3 cm thick polystyrene sheets on the outside insulate its sidewalls. The insulation is kept while the tank is filled with the density-stratified fluid, and carried out from the side facing the camera, to allow its optical access. The lower boundary can be kept to a given nearly constant temperature by means of a circulating water bath, separated from the fluid through a metal sheet. A stable stratification, e.g. a positive vertical temperature gradient, is obtained by means of two connected tanks. The fluid is initially equally distributed into two identical tanks. The temperature inside the tanks is kept constant and equal to: T_w (“warm” tank) and T_c (“cold” tank). An agitator is placed within the cold tank to homogenize the temperature. A tube, connecting the “cold” tank and the test section, fills the latter with a temperature-stratified working fluid. The container is filled till a height of 18 cm.

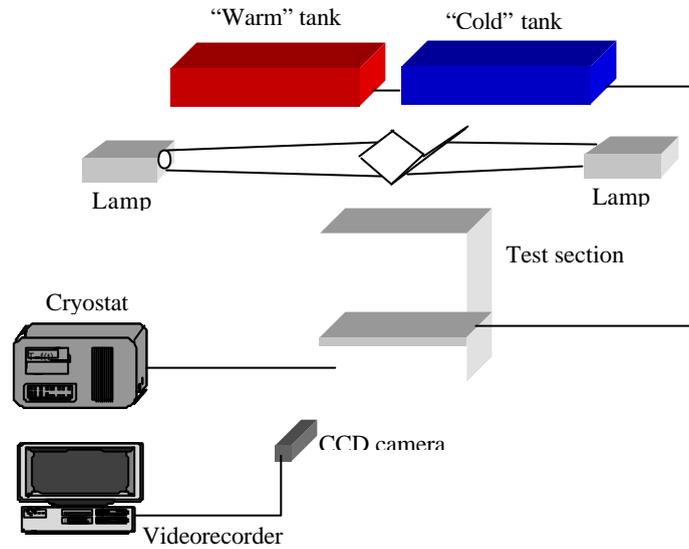


Figure 1 - Experimental set-up

Images of well reflecting tracers (pollen particles with an average size equal to $d_p = 80 \mu\text{m}$) are recorded using a CCD camera. The fluid is seeded during the test section filling up. The seeding is insert within the “cold” tank. Two 250 W arc lamps illuminate the measuring volume. A beam stop allows the depth of the illuminated area to be controlled. Thermocouples are used for measuring the mean temperature at various heights. Several profiles are detected through mounting a thermocouple on a support, that moves upwards and backwards by means of a motor with its gear drive located outside the test section and controlled via software. At the upper boundary, the temperature is maintained at a constant value through an isolating *polystyrene* sheet. At the lower boundary, before the heating starts, the temperature is maintained at a fixed value T_0 , approximately equal to the cold tank temperature. Table 1 presents typical values for the experiments carried out.

Table 1 Features of the experiments

EXPERIMENT #	a_0 (m / K)	T_0 (K)	T_{final} (K)
N° 1	0.011	284.95	293.92
N° 2	0.020	286.68	292.58
N° 3	0.015	285.85	294.63
N° 4	0.024	293.86	299.85

N° 5	0.034	294.00	299.00
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The thermal convection is started at time $t=0$ upon replacing the cool water circulating behind the lower boundary with water at temperature almost equal to the larger achieved within the test section. The temperature at the bottom, T_c , increases slowly and its value gradually approach the final value, $T_{c\,final}$.

The acquisition procedure can be divided into different steps: at first images are recorded on a tape, then the images are digitised and temporarily stored on the mass memory of a computer (576x720 pixels as resolution), next they are analysed to detect particle locations and trajectories (PTV) or features and trajectories (FT).

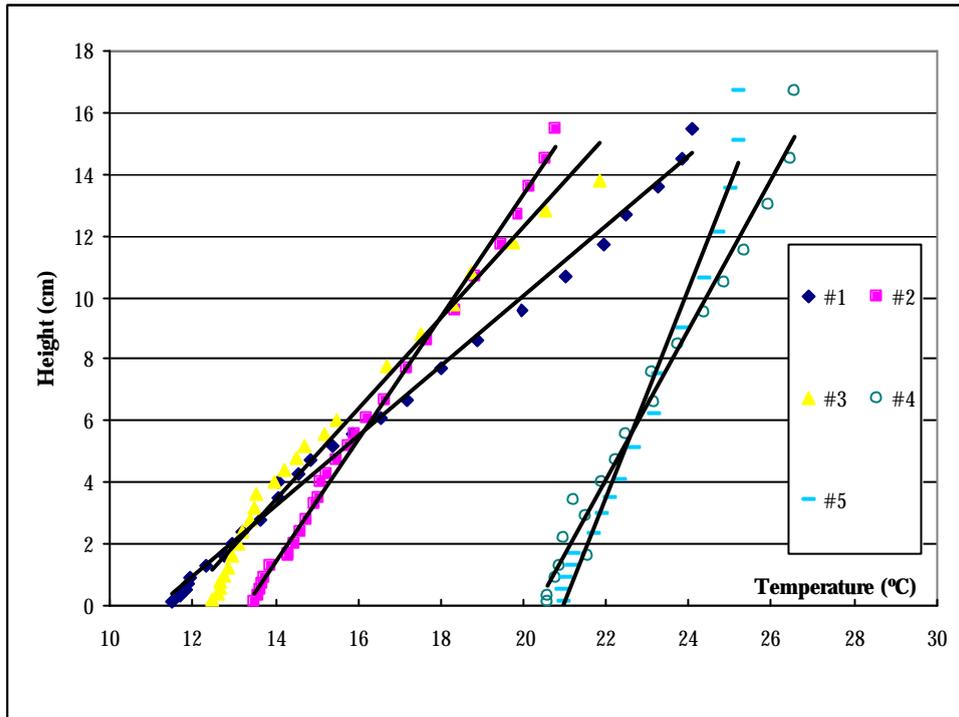


Figure 2 - Final stratification profiles for the three experiments

3. RESULTS AND DISCUSSION

3.1 Temperature profiles

During each experiment, a set of 29 thermocouples aligned along the vertical direction detects the temperature with one-second time resolution. Those values are averaged along 30 seconds to obtain successive mean temperature profiles. Figure 2 displays several final stratification profiles for the set of experiments listed in Table 1.

Five different sets of initial conditions are investigated. The mean initial temperature gradient, α_0 , is determined by taking the best fitting straight line of the initial mean profile. Figure 3 displays the evolution of the temperature along the vertical direction and as a function of time for the experiment 1.

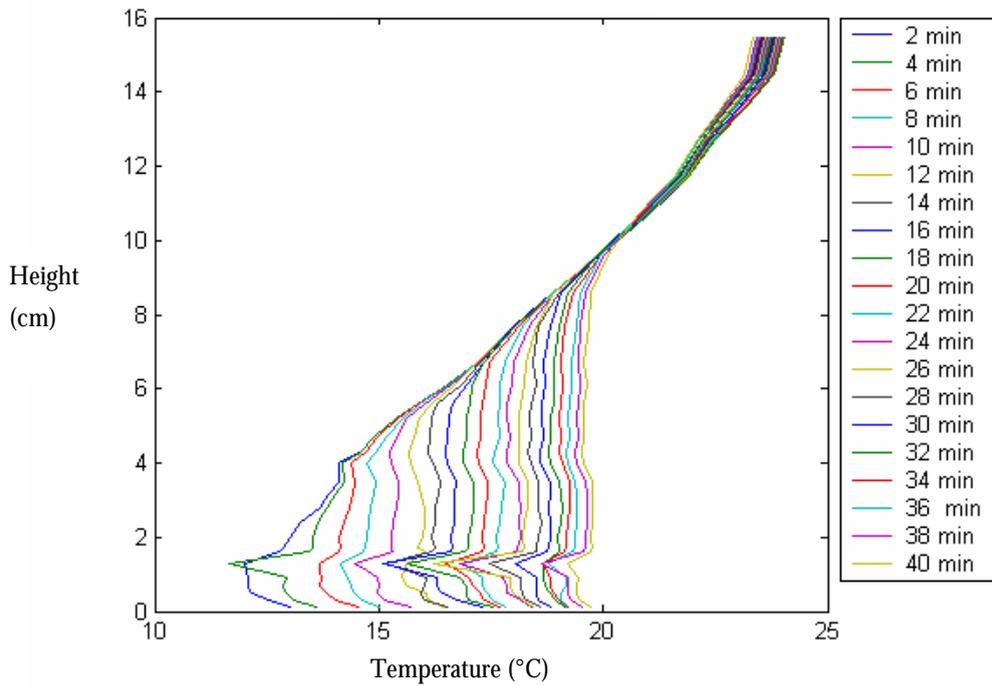
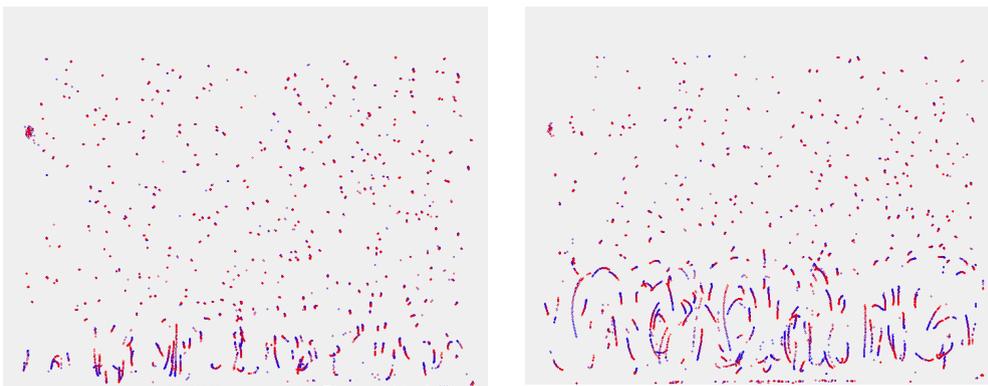


Figure 3 - Vertical profiles of temperature for experiments 1

3.2 Centroids individuation and fluid particle tracking

PTV is employed to individuate barycenters and to reconstruct tracer particle trajectories inside the test section.



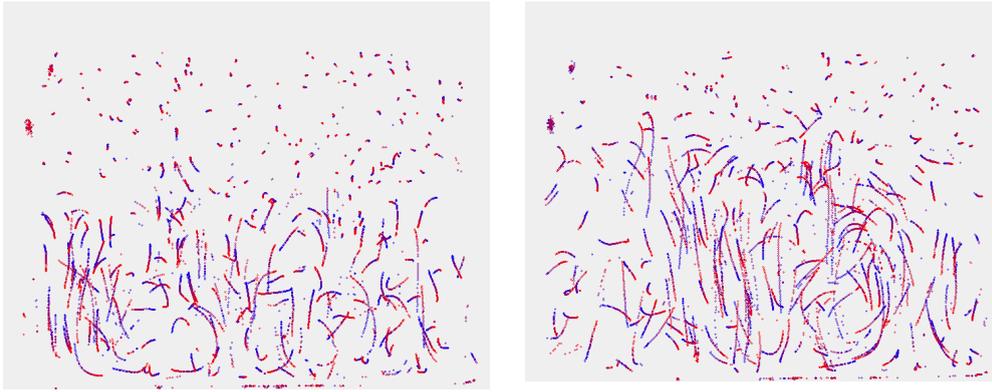
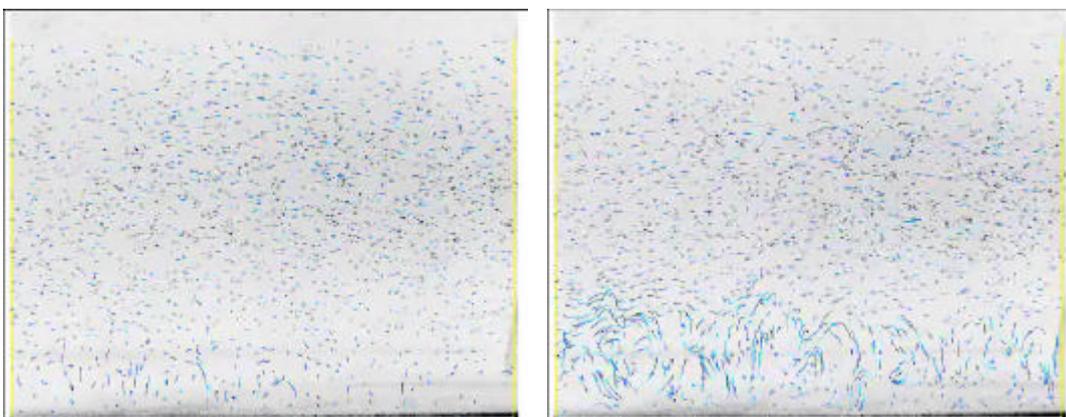


Figure 4 – Centroids reconstructed through PTV during the mixing phenomenon (both the effects of penetrative convection and internal waves are depicted)

The particle detection algorithm is based on image thresholding (based on the image histogram) and labeling of lighted pixels. The barycenter location is determined with a sub-pixel accuracy. The set of particle image locations is used as input data for the tracking algorithm. The first two points belonging to a trajectory are chosen within a circle of fixed radius. This condition is equivalent to assuming a maximum velocity in the investigated flow. To add spots to the two-point trajectory the nearest neighbor principle is employed. When ambiguities arise, the criterion of “minimum acceleration” along the trajectory passing through the points in question is employed. Figure 4 displays centroids reconstructed inside both the stable and the unstable layers as they evolve with time. Each picture presents the centroids reconstructed analyzing 50 frames. Different pictures refer to different instant of times, being time zero the beginning of the mixing process. The features of the experiments are the same of Experiment 2 (see Table 1). Looking at Figure 4 we can conclude that the convective motions grow starting from the lower warm boundary and give rise to upward domes. They coalesce one with the others, forming larger structures with higher velocity. Tracking fluid particle motion, its features can be observed. After a particle leaves the boundary, it travels an upward portion till the inversion layer is reached. At this point, the velocity vertical component goes to zero and changes sign. The particle will now travel the mixing layer downward. Fluid particles belonging to the mixing layer remain trapped within it. After the turbulent region has reached a consistent height, the tracer particles belonging to the interface between the stable and unstable layers start moving along oscillating trajectories (internal waves). As time passes, internal waves are present overall the stable layer. The same particles describing oscillating trajectories are later entrained inside the turbulent fluid.

3.3 Feature extraction and tracking

Feature Tracking matches by selecting image features and tracks them from frame to frame. *Figure 5* presents features tracked by Feature Tracking during mixing. Internal waves are tracked as well. The evolution of the phenomenon can be detected as well.



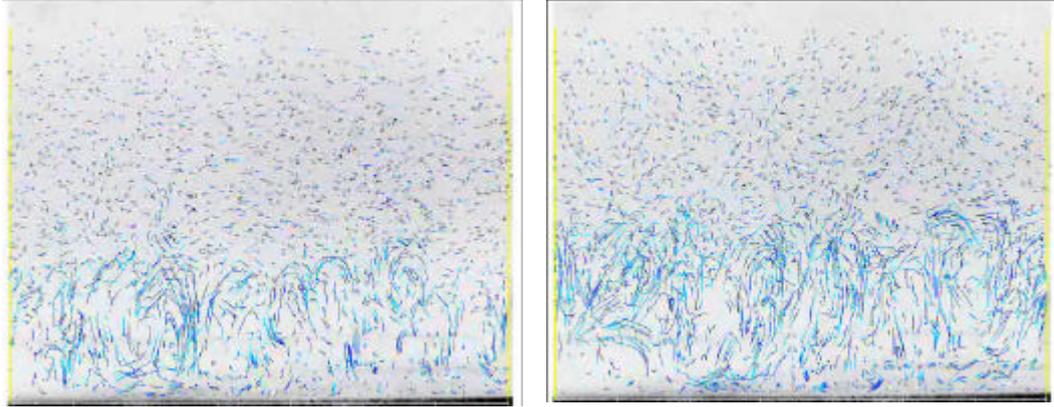


Figure 5 – Features reconstructed through FT during the mixing phenomenon (both the effects of penetrative convection and internal waves are depicted)

3.4 Methods for mixing layer height detection

Several methods were employed to detect the mixing layer height (h). The results obtained from each method were then overlapped to test accuracy. To describe the first methods, referred to as “method of temperature profile”, we need to introduce the typical temperature profile at a given time along the vertical direction. The volume close to the lower boundary is characterised by a constant mean temperature while the upper volume, the stable layer, presents the initial linear stratification (Figure 6).

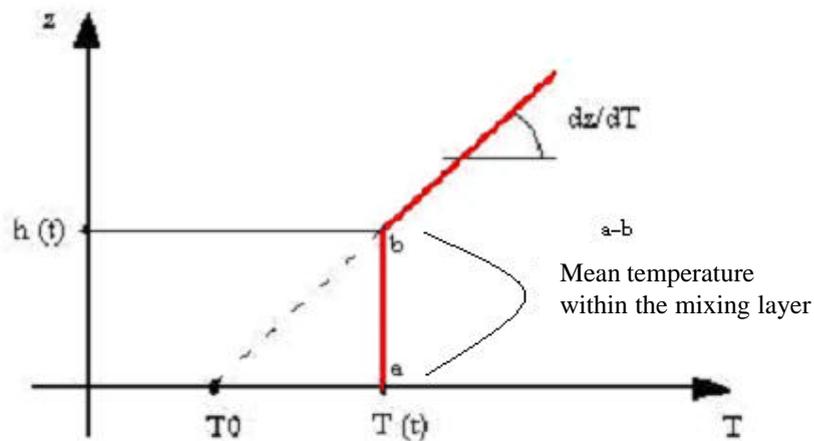


Figure 6 – Vertical temperature profile within the test section

This theoretical behaviour is accomplished by our experimental data (Figure 3). The height for each time is detected through evaluation of the point ‘b’ in Figure 6.

On the other hand, the temperature within the mixing layer, $T_w(t)$, is related to h through a theoretical relation:

$$h(t) = a_0 \cdot (T_w(t) - T_0)$$

As a consequence, knowing the temperature within the mixing layer, the height can be detected applying the relation above (“method of theoretical height”).

The third method (“method of the velocity variance”) consists in reconstructing the average horizontal and vertical velocity components along the vertical profile as a function of time and employing the horizontal homogeneity

hypothesis. The mixing layer is characterised by larger values of the variance of both components than within the stable layer.

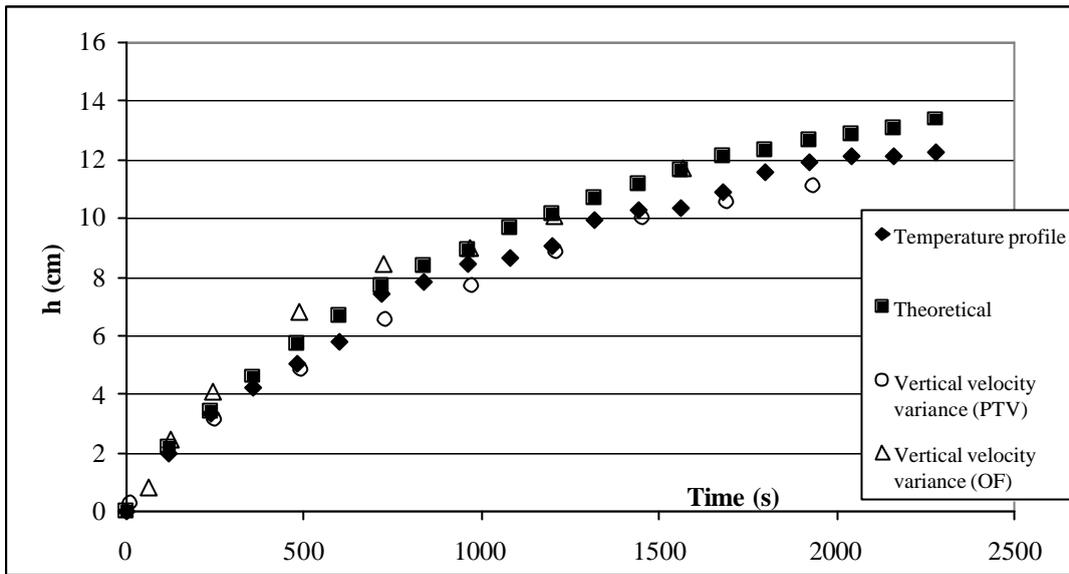


Figure 7 – Vertical temperature profile within the test section

Figure 7 displays the superposition of the three methods (the vertical velocity variance was reconstructed with both PTV and OF data). The curves are very close by.

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