A Wind Tunnel Study of Thermally Stratified Boundary Layers over Rough Surfaces

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Abstract. *The effect of stratification on the features of boundary layers developing over rough surfaces has been studied experimentally. The results are compared with the classical theories of other authors for two different stability regimes: stable, and unstable flows. A description of the apparatus together with the measuring technique is given in a specific section. The parameters of the boundary layer are qualified through: growth, structure, equilibrium, turbulent transport of heat and energy spectrum.*

Keywords. *Stratification, roughness, turbulence, wind tunnel, thermal anemometry.*

1. Introduction

Thermal stratification is known to play a major role in the physical processes that take place in the atmosphere. Of particular concern to researchers has been the study of the diffusion of pollutants in the atmosphere under the combined effects of stratification and orography; this very often leads to hazardous environmental conditions.

Because investigating naturally occurring density stratified flows is normally a very difficult and costly affair, one attractive alternative is to try to reproduce similar conditions in the laboratory. This, in theory, would favor the experimenter in view of the controlled conditions and easy access instrumentation. As a result, low-speed wind tunnels have largely been used in the past to study pollutant dispersion. Unfortunately, most studies have been carried out for flows under adiabatic conditions and over smooth surfaces.

The purpose of this work is to investigate experimentally the effect of density stratification on the characteristics of boundary layers developing over rough surfaces. The effects of unstable and stable conditions on the flow will be examined. Requiring the following criteria to be met assessed the quality of the simulation: Reynolds number independence, mean velocity profiles and turbulence intensities.

The paper will show how heating through electrical resistances both, the floor and the incoming air, controls the boundary layer that is formed in the wind tunnel. The resistances can furnish an increase in floor temperature of up to 100 ^{o}C above ambient temperature and can be applied over a 6000 mm long surface with a controlled variation of 2 ^{o}C. The incoming air is heated by forcing the flow through a set of 10 electrical heating elements that can be operated individually. The system can then be used to produce, unstable, neutral and stable boundary layers.

The rough surface was constructed with a well-defined geometry. Previous authors (see, e.g., Perry and Joubert(1963), Antonia and Luxton(1971,1972), Wood and Antonia(1975)) have classified rough surfaces into two types of surfaces: 1) “K” type rough surfaces and, 2) “D” type rough surfaces. In cases where the nature of the roughness can be expressed with the help of a single length scale - the height of the protrusions, K - the surface is termed of type “K”. Flows, on the other hand, which are apparently insensitive to the characteristic scale K, but depend on other global scale of the flow, are termed “D” type flows. This is the case, for example, of a roughness geometrically characterized by a surface with a series of closely spaced grooves within which the flow generates stable vortical configurations. Here, only a K-surface will be investigated.

The experimental investigation of turbulent boundary layers under unheated, steady flow conditions is a relatively common exercise in laboratories. For most studies, Hot-Wire Anemometry (HWA) is the principal research tool. The very well known advantages of this superb measuring technique make it a must for turbulence research. Thus, it is only natural to realize that a host of articles have been dedicated in literature to this technique. However, all measuring techniques have their problems and application restrictions and HWA is not free from them. For example, dealing with flows in which the temperature of the fluid varies with either time or position may pose severe difficulties, which are hard to overcome. That is certainly a good explanation for the fact that only a handful studies are available for unsteady, heated flows. In fact, most of the HWA literature is restricted to situations where only a slight compensation for ambient temperature deviations is needed to correct the hot-wire signal. Bremhost(1985) reviewed difficulties and methods associated with correct velocity measurements in heated flows using hot-wire anemometers and proposed a method for automatic compensation to give a corrected, instantaneous velocity signal by use of a hot and cold-wire anemometers simultaneously. The method was limited to flows with a spectral content below the corner frequency response of the cold wire.

Unfortunately, in real atmospheric flows, large temperature gradients are present in the flow resulting in conditions that require the simultaneous measurement of instantaneous velocity and temperature for a correct characterization of any phenomena under study. In this work, we also show how an extension of resistance wires for the investigation of the influence of the temperature field in the properties of boundary layers can be made so as to obtain a better understanding of the mixing processes involved in such problems.

2. Short literature review

Before we begin our discussion of the problem, let us first present the reader with a short literature review on stratified flows over rough surfaces.

Wind tunnels specially designed for the study of atmospheric flows are normally very large in size and expensive. The minimum required length to simulate a qualified flow configuration is normally agreed in literature to be 10 meters. As such, many facilities have a test section in excess of 20 meters. Typically fitted with a velocity profile generating cart, three independent temperature systems, surface roughness, wind orientation, variable area source and sampling grid floor panels, these tunnels are complex and difficult to operate. Thus, several articles have been published in the past to account for the features of laboratory produced flows. Examples are the articles of Webster(1963), Rey et al.(1979), Ogawa et al.(1981), Arie et al.(1981), Granger and Meroney(1994), Fedorovich et al.(1996), Robins et al.(2001a, 2001b) and Briggs et al.(2001) among others. Please note that these selected articles cover four decades.

In the early sixties, Webster designed and constructed a very simple wind tunnel to study turbulence in a density-stratified flow. Most of the paper concerned the description of the apparatus and of the mean temperature and velocity gradients in the tunnel, together with an explanation of a technique devised to measure low wind speeds based on the shedding of vortices by a circular cylinder. In the remaining of the work, details of the turbulence structure were considered. Due to the short linear dimensions of the apparatus, disappointing results were obtained since steady state conditions could not be achieved. Webster indicated that a doubling or trebling of the linear dimensions of his tunnel would be necessary.

While some successful attempts were made at generating artificially thickened turbulent boundary layers to simulate neutral flows in short wind tunnels (see, e.g. Arie et al.(1981)), other authors studied the effect of buoyancy on the characteristics of boundary layers developing over smooth and rough surfaces on larger facilities. The wind tunnel of Rey et al.(1979) had a 1 m wide x 1.2 m high x 10 m long test section with a wall that could be heated up to 100 ^{o}C and made rough by fitting transverse loop-hole bars. The study speculated on the limitations of the Monin-Obukhov similarity theory as applied to wind tunnels. The paper discussed the combined effects on the turbulence of unstable temperature stratification and variations in the Reynolds number. The authors showed that buoyancy acts mainly on the temperature and on the vertical velocity spectra. The turbulence quantities were measured by means of a three-wire probe, a combination of an X-wire with a single wire probe. The X-probe operated by two DISA 55M01 HWA yielded the two velocity components. The single wire was fed to a Constant Current Anemometer (CCA).

The effects of neutral, strongly unstable and strongly stable stabilities on flows were examined by Ogawa et al.(1981). The specially designed facilities consisted of a vertical, closed-circuit, single return wind tunnel, completely enclosed in a temperature controlled building. The test section was 3x2.4x24 m. Five different methods could be used to measure velocities; temperature measurements were made through five other different methods. Concentration measurements were made by four different methods. The authors showed that in the stable case, turbulence is damped near the ground yielding a wavy streamline; in the unstable case, on the other hand, a large convective eddy motion was observed.

Experimental techniques to model stably stratified flows have also been examined by Grainger and Meroney(1994). The experiments were performed in a large wind tunnel (test section: 10 m wide x 5 m high x 40 m long) where all heating was provided by electrical resistors placed along a false wind tunnel roof. The paper presented mean velocity and temperature profiles as well as estimation of the bulk Richardson number. Measurements were made with a TSI HWA system and thermocouples.

To simulate the typical convective conditions in the lower atmosphere, where a convective mixed layer developing over a heated surface is capped by a temperature inversion, Fedorovich et al.(1996) designed a special wind tunnel. The wind tunnel is of the closed circuit type, with a test section 1.5 m wide, 1.5 m high and 10 m long. The flow velocity components were measured with a laser Doppler system; the temperature was measured with a resistance-wire technique. The wind tunnel data when compared with results from atmospheric, water tank and numerical studies of the convective boundary layer showed the important dependence of the turbulent statistics in the upper part of the layer on the entrainment and the surface shear.

All above mentioned studies, but Rey et al.(1979), were performed for flows over smooth surfaces. Despite their undisputed importance, clearly, a more comprehensive study for flows over rough surfaces was lacking.

Recently, some cooperative research programs have turned their attention to flows over rough surfaces. Robins et al.(2001a, 2001b) and Briggs et al.(2001) have discussed the flow of a boundary layer over a rough surface. Specifically, they studied the dispersion of dense gases in neutral and stable boundary layers. Mean velocity and temperature, turbulent normal and shear stresses, temperature fluctuations and heat fluxes were measured and used to demonstrate that a moderately stable atmospheric boundary layer was successfully simulated in a wind tunnel. Entrainment velocities were then calculated from the concentration field development and correlated with the Richardson number. Higher entrainment speeds were observed in the stable boundary layer than in the neutral boundary layer.

Cataldi et al.(2001) showed how, in a short wind tunnel environment, boundary layers with different states of stability regime could be produced. The work analyzed the dynamic and thermal characteristics of different types of thick, artificially generated, turbulent boundary layers. The paper aimed at showing how a simple combination of spires and trips placed upstream of the test station could be used to yield a qualified thick boundary layer.

Venkatram(1976) developed a slab model of the boundary layer to study the dynamics of the internal boundary layer associated with changes in surface temperature. The governing equations were solved in a Lagrangian framework to show that mixed-layer growth was enhanced by: i) an increase in surface roughness, ii) an increase in the surface temperature change, and iii) a decrease in the horizontal velocity. The author found that the vertical velocity induced by variations in the horizontal velocity could play an important role in controlling the expansion of the mixed layer. The study also involved the formulation of a model by simplifying the governing equation.

A simple scaling framework for the evolving atmospheric boundary layer was proposed by Kitaigorodskii and Joffre(1988). The theory was based on a simple parametrization of the vertically-integrated dissipation term in the turbulent kinetic energy equation. The introduced scaling was valid for both stable and unstable flows.

The basic characteristics of the atmospheric surface layer were reviewed by Högström(1996). The paper carefully analyzed the validity of the von Karman constant for geophysical flows besides testing various published formulae for the non-dimensional wind and temperature profiles. For unstable stratification, the various formulae for the temperature profiles were observed to agree to within 10-20%. In very unstable conditions, results were conflicting. The Kolmogorov streamwise inertial subrange constant was also investigated as well as the turbulence kinetic energy budget.

Garratt(1989) reviewed relevant work on the internal boundary layer associated with: i) small-scale flow in neutral conditions across a sudden change in surface roughness, ii) small-scale flow in non-neutral conditions across a sudden change in surface roughness, temperature or heat flux, and iii) mesoscale flow.

Mahrt(1998) discussed the various characteristics of different stability regimes of the stable boundary layer. The traditional layering was examined, as a function of the roughness sublayer, surface layer, local similarity, z-less stratification and the region near the boundary layer top. Mahrt argued that, in the very strong case, turbulence may be generated by shear associated with a low level jet, gravity waves or meandering motions. Under this condition the traditional boundary layer approximation breaks down.

3. The stratified turbulent boundary layer

For a neutral atmosphere the classical logarithmic wind profile is observed to occur. As the atmosphere becomes stable or unstable, the profile departs from its logarithmic shape so that appropriate corrections have to be applied.

For the diabatic wind profile, the modified logarithmic profiles can be written as follows.

a) Stable flow.

$$\bar{u}(z) = \frac{u_t}{k}\left(ln\frac{z}{z_0} + g_m\frac{z}{L}\right) \tag{1}$$

$$\bar{q}(z) = \bar{q}(z_0) + a_k\frac{q_t}{k}\left(ln\frac{z}{z_0} + g_h\frac{z}{L}\right) \tag{2}$$

where u_τ the friction velocity, z_0 is the roughness length, α_h = 0.74 (Businger et al.(1974)) or 1.0 (Dyer(1974)), t_τ is the friction temperature, γ_m=γ_h = 4.7 (Businger et al.(1974)) or 5.0 (Dyer(1974)).

b) Unstable flow.

$$\bar{u}(z) = \frac{u_t}{k}\left(ln\frac{z}{z_0} - y_m\frac{z}{L}\right) \tag{3}$$

$$\bar{q}(z) = \bar{q}(z_0) + a_h\frac{q_t}{k}\left(ln\frac{z}{z_0} - y_h\frac{z}{L}\right) \tag{4}$$

where

$y_m = 2\ ln((1+x)/2) + ln((1+x^2)/2) - 2\ tan^{-1}\ x + x/2,$

with $x = (1 - b_m(z/L))^4$ and b_m = 15 (Businger et al.(1971)) or 16 (Dyer(1974)), and

$y_h = ln((1+y)/2)$

with $y = (1 - b_h(z/L))^2$ and b_h = 9 (Businger et al.(1971)) or 16 (Dyer(1974)).

One of the purposes of this work is to test the above equations under our flow stratification conditions.

4. Experimental apparatus and instrumentation

The general requirements for similarity of flows were comprehensive discussed in Cataldi et al.(2002). For this reason, the discussion will not be repeated here. However, a few reminders will be brought about here.

The requirements for geometric, dynamic and thermal similarity must be obtained by direct inspection of the equations of motion. Upon consideration of the equations of conservation of mass, momentum and energy, one can show that five dimensionless groups have to be matched to guarantee exact similarity:

Rossby Number; $R_o = U_0 / L_0\ \Omega_0$,
Reynolds Number; $R_e = U_0\ L_0 / u_0$,
Richardson Number; $R_i = |(\Delta)_0 T_0| (L_0 / U_0^2) g_0$.
Prandtl Number; $P_r = u_0 / (k_0 / r_0\ C_{p0})$,
Eckert Number; $E_c = U_0^2 / C_{p0}\ (\Delta T)_0$.

Unless some rotation is imposed on the wind tunnel, Rossby number similarity will never occur; Reynolds number similarity is also never achieved. If air is used as the working fluid in the wind tunnel, Prandlt number similarity is immediately achieved. The influence of Eckert number is not relevant. Finally, Richard number similarity can be obtained in a wind tunnel since in the atmosphere $-1 < R_i < 1$.

We will now describe the experimental facilities.

The general features of the atmospheric wind tunnel where the experiments were performed are:

- Circuit: open.
- Test section: 0.67 m high, 0.67 m wide and 10 m long.
- Wind speed: continuously variable from 0.5 to 3 m/s.
- Longitudinal pressure gradient: adjustable to zero by means of an adjustable ceiling.
- Turbulence intensity: 2%.
- Surface heating capacity: 1.1 kW per m^2.
- Length of wall heating section: 6 m.
- Wall temperature: variable from 21 to 100^o C.
- Number of resistances used to heat the incoming air: 10.
- Resistance capacity: 2 kW.

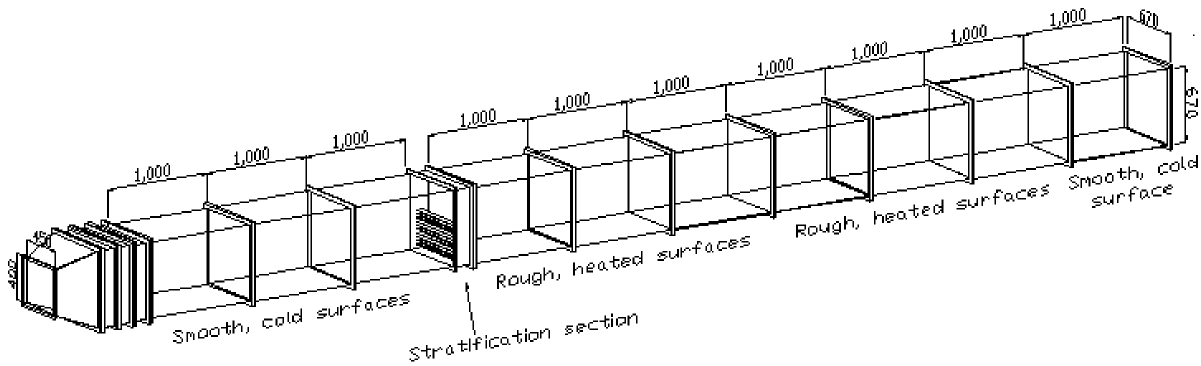

Figure 1. Sketch of atmospheric wind tunnel. Dimensions in millimeters.

Fig. 1 shows a sketch of the wind tunnel. Fig. 2 shows pictures of the actual wind tunnel and of the heating system.

The rough surface was constructed with equally spaced transversal rectangular slats. The dimensions of the roughness elements are shown in Fig. 3 were K denotes the height, S the length, W the gap, and λ the pitch. In constructing the surface, extreme care was taken to keep the first roughness element always depressed below the smooth surface, its crest kept aligned with the smooth glass wall surface.

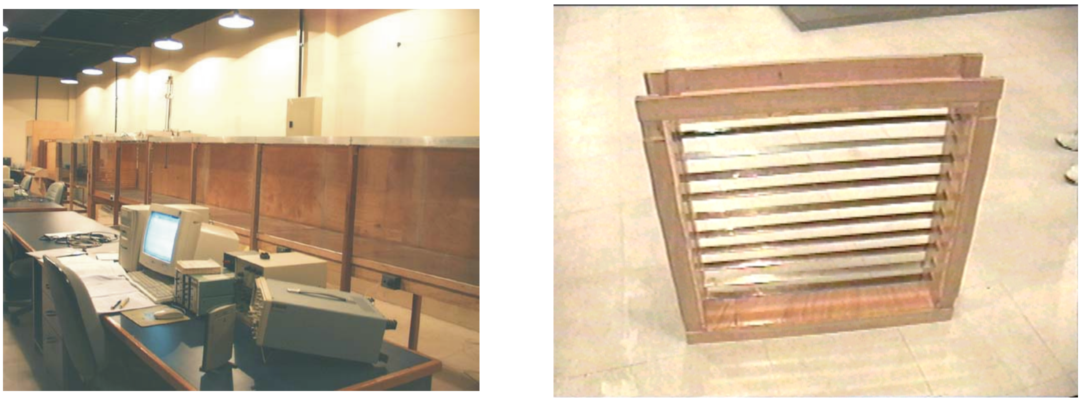

Figure 2. Picture of atmospheric wind tunnel and of heating system.

The geometry of the rough elements is shown next in Fig. 3.

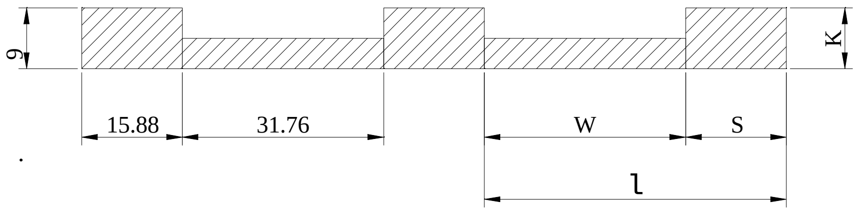

Fig 3. Roughness geometry. Dimensions in milimetres.

An appropriate data reducing method for measurements on flows with temperature variation was discussed previously in Loureiro et al.(2002). The paper dealt specifically with low velocity flows subjected to large temperature gradients. The work developed an accurate procedure to minimize experimental errors in HWA velocity measurements in stratified flows. Here, we will use that particular method.

In all experiments, simultaneous measurements of streamwise velocity and fluctuating temperature were obtained by using thermal anemometry. The measurements accounted for any large temperature variation in interpreting the sensor response. To perform the measurements a temperature-compensated Dantec probe, model 55P76, was used. This probe consists of two sensor elements: a hot-wire and a resistance-wire, usually called cold-wire, situaded 2 mm below and 5 mm downstream of the former. Both sensors are Pt-plated tungsten wires, 5 μm in diameter, overall length of 3mm and sensitive wire length of 1.25 mm. They are copper and gold plated at the ends to approximately 30 μm. They were connected respectively to a constant temperature bridge, Dantec 55M10 and to a constant current bridge, Dantec 56C20.

Among the several possible methods that can be used to characterize the dependence of the signal of a thermal anemometer on velocity and temperature, we will consider a direct calibration of the variation of the anemometer output voltage, E, with the velocity, U, and the fluid temperature, T_a, for a given hot resistance setting, R_w. This method is complex to implement but is also very accurate, so that it will be adopted in this work. The calibration data obtained by this method can reveal to what an extent other methods can be used to evaluate the temperature and velocity sensitivity of a hot-wire probe operated in the CT mode. A similar approach was adopted by Lemieux and Oosthuizen(1984). They expressed their calibration relationship in the form of linear curves. For each value of a given T_a they determined the values of A, B and n in King's law by a least squares curve fitting procedure. In their subsequent signal analysis the optimum value for n was selected as being the average value from their four calibration curves. The corresponding calibration coefficients A and B were found to vary linearly with T_a. Other authors have also reported a linear variation of E_2 with T_a. In conclusion, most experimental investigations of this type, covering small or moderate variations in T_a, have demonstrated that the output signal from a hot-wire probe operated in the constant temperature mode is directly proportional to a product of the temperature difference (T_w -T_a) and a function of the velocity. Loureiro et al.(2002) showed that even under large temperature gradient conditions this method could be used to evaluate flow velocity; hence, we found licit to adopt this technique here.

For the present measurements, a DANTEC 55M01 main unit together with a 55M20 constant current bridge was used. The boundary layer probe was of the type 55P76. A Pitot tube, an electronic manometer, and a computer controlled traverse gear were also used. In getting the data, 10.000 samples were considered. The reference mean temperature profiles were obtained through a chromel-constantan micro-thermocouple mounted on the same traverse gear system used for the hot-wire probe. An uncertainty analysis of the data was performed according to the procedure described in Kline(1985). Typically the uncertainty associated with the velocity and temperature measurements were: U = 0.0391 m/s precision, 0 bias (P=0.95); T = 0.2 ^oC precision, 0 bias (P=0.99).

5. Results

The experiments were performed, as said before, in the atmospheric wind tunnel of PEM/COPPE/UFRJ. As illustrated in Fig. 1, from the total 10 m length of the tunnel, the first 3 m are fitted with a smooth glass wall that is kept at ambient temperature. The stratification section consisting of 10 electrical resistances follows next; it is capable of heating the flow differentially up to 100 ^oC. The next 6 m are fitted with the roughness elements; they can be heated up to 100 ^oC by six 1-meter panels that can be controlled individually by a series of resistances. The total heating capacity of each panel is about 7 kW/m^2. The whole facility is capable of developing gradients of up 50 ^oC at uniform mean speeds in the range 1.5-2.5 m/s, so as to generate different levels of instability.

Four measuring stations located respectively at 8.2, 8.4, 8.6, and 8.8 m from the entrance section were considered.

The measured global parameters for the stable boundary layer are shown in Table 1, where L denotes de Monin-Obukhov length, R_i the Richardson number, T_τ the temperature velocity, U_τ the friction velocity, δ the boundary layer thickness, G the Clauser factor and ε the error in origin.

Table 1. Turbulent boundary layer parameters for stable conditions.

Stable Boundary Layer	Station 1 8.2 m	Station 2 8.4 m	Station 3 8.6 m	Station 4 8.8 m
L (m)	7.79	10.322	23.9	22.9
R_i	0.012	0.009	0.004	0.005
T_τ (Kelvin)	0.170	0.166	0.188	0.200
U_τ (m/s)	0.117	0.109	0.107	0.112
δ_τ (m)	0.13	0.14	0.15	0.15
δ_υ (m)	0.13	0.14	0.15	0.15
G (Clauser factor)	6.343	6.990	7.027	6.810
ε (m)	0.0047	0.0047	0.0047	0.0047

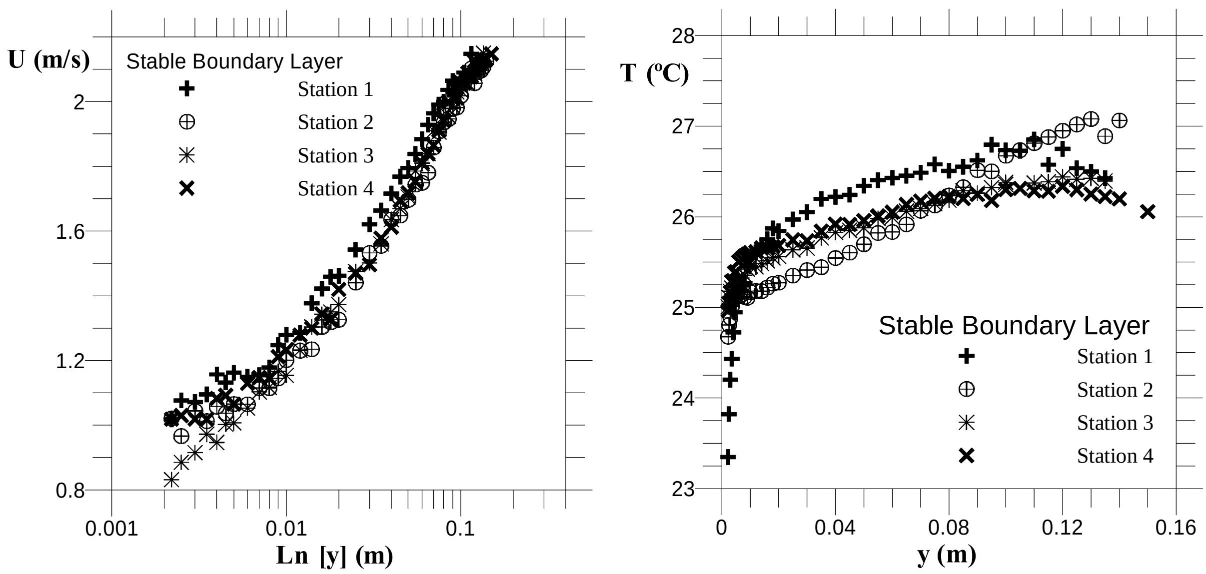

Figure 4. Velocity and temperature profiles for stable conditions in dimensional coordinates.

The stable velocity and temperature profiles are shown in dimensional form in Fig. 4.

The error in origin, ε, was estimated by the procedure of Perry and Joubert(1963). In the Perry and Joubert method, arbitrary values of ε are added to the wall distance measured from the top of the roughness elements and a straight line is fitted to the log-law region. The value of ε that furnishes the best-discriminated logarithmic region is then considered to be the correct value for the error in origin.

Thus, to determine the error in origin, the velocity profiles were plotted in semi-log graphs in dimensional coordinates. Next, the normal distance from the wall was incremented by 0.1 mm and a straight line fit was applied to the resulting points. The best fit was chosen by searching for the maximum coefficient of determination, R-squared. Other statistical parameters were also observed, the residual sum of squares and the residual mean square. Normally, a coefficient of determination superior to 0.99 was obtained. Having found ε (see Table 1), we can now use the gradient of the log-law to determine the friction velocity.

The effects of the roughness on the velocity and temperature profiles are clearly observed in Fig 4. The mild stability furnishes values for the global and local flow parameters that are very similar to the neutral values, making it difficult to establish any relevant conclusion on the interrelation between stability and roughness on the boundary layer properties.

The Businger(1971) profile is compared with our data for stable flow in Fig. 5. Despite some departure from the temperature data in the outer region of the flow, the agreement is reasonable.

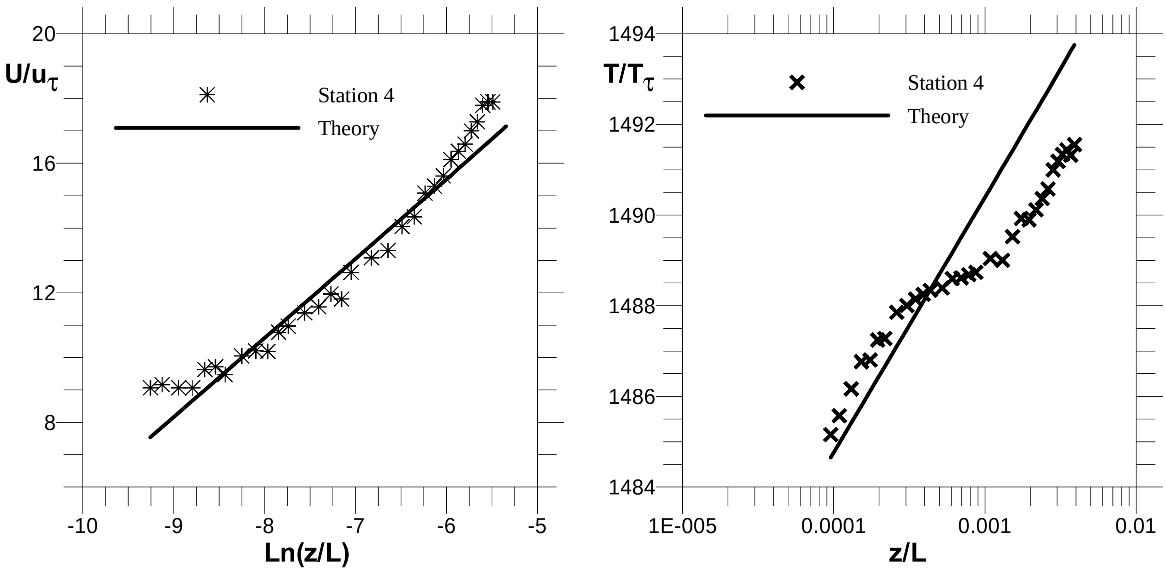

Figure 5. Velocity and temperature profiles in non-dimensional coordinates. Stable conditions.

The measured global parameters for the unstable boundary layer are shown in Table 2, where the notation used in Table 1 has been repeated.

All results are within the expected trend except for ε, the error in origin for the velocity profile. Under unstable conditions the distortion of the velocity profile was such that non-physical values of ε were found.

Table 2. Turbulent boundary layer parameters for unstable conditions.

Unstable Boundary Layer	Station 1 8.2 m	Station 2 8.4 m	Station 3 8.6 m	Station 4 8.8 m
L (m)	-1.87	-1.79	-1.90	-1.85
R_i	-0.092	-0.084	-0.083	-0.081
T_τ (Kelvin)	-1.830	-1.984	-2.068	-1.846
U_τ (m/s)	0.101	0.100	0.977	0.093
δ_τ (m)	0.24	0.21	0.22	0.21
δ_υ (m)	0.24	0.21	0.22	0.21
ε (m)	0.03	0.03	0.03	0.03
ε_t (m)	0.0047	0.0031	0.0032	0.0047

This effect, to our understanding, was provoked by the unstable stratification of the flow, resulting in much larger values of the friction velocity.

The Businger(1971) profile is compared with our data on unstable flow in Fig. 7. Here, the agreement seems superior than that for the stable case.

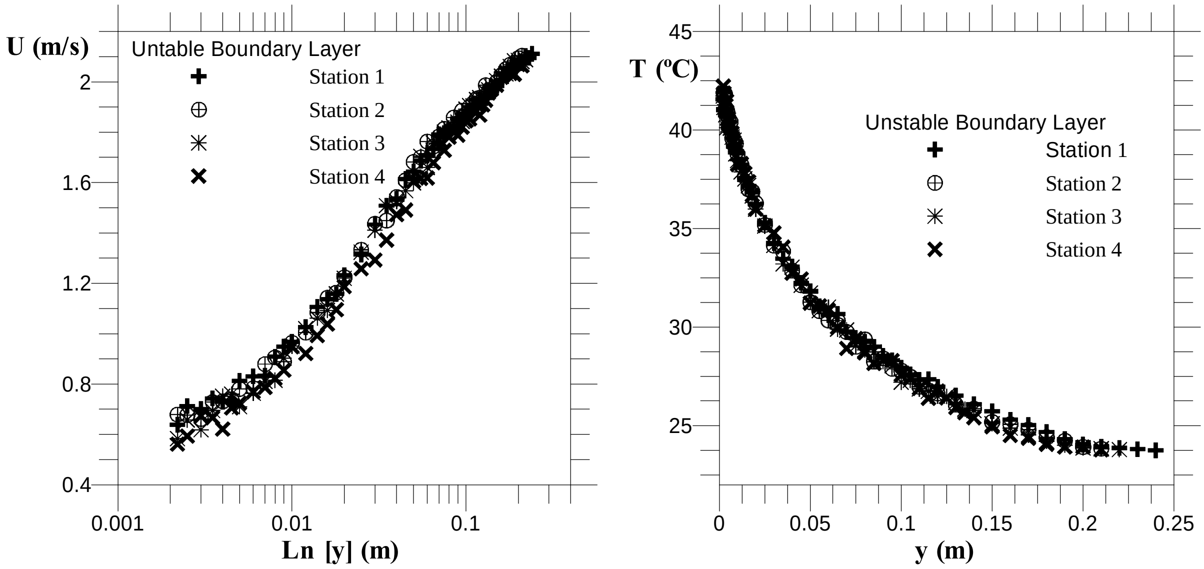

Figure 6. Velocity and temperature profiles for unstable conditions in dimensional coordinates.

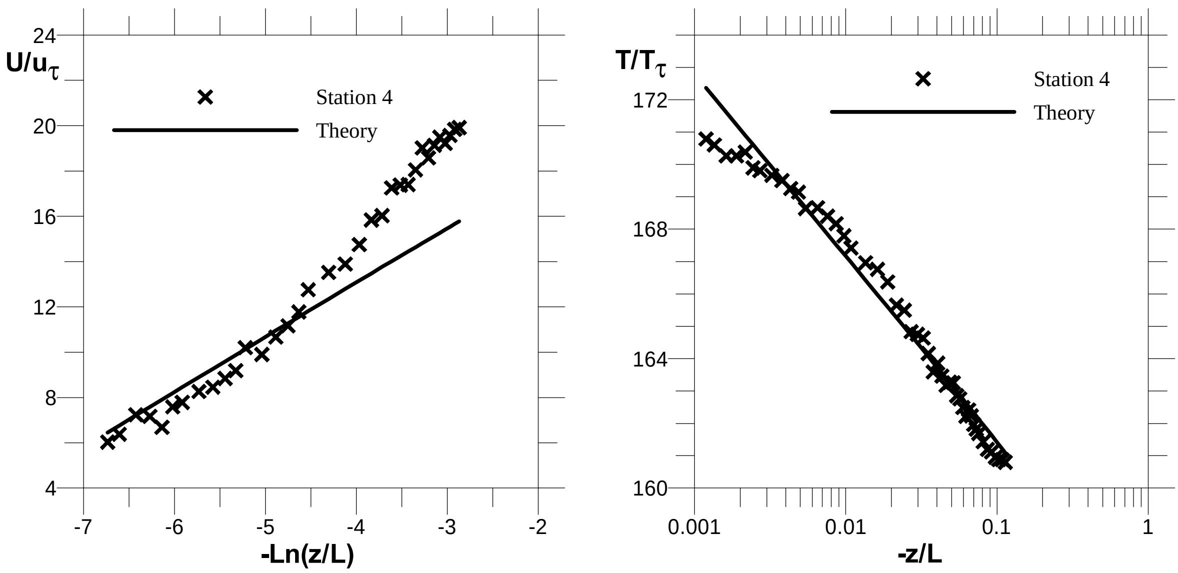

Figure 7. Velocity and temperature profiles in non-dimensional coordinates.

Our most interesting results, however, were saved for the turbulence data. Figures 8 and 9 show the velocity and temperature fluctuations for both stable and unstable conditions. The pattern is clear: unstable density stratification increases the velocity and the temperature fluctuations whereas stable density stratification has the opposite effect. Furthermore, under stable conditions the temperature fluctuation exhibits a point of minimum near to the wall. This is exactly the opposite behaviour of the temperature fluctuation under unstable condition, which exhibits, on the other hand, a point of maximum. This behaviour has been accounted here for the first time and seems to be associated to both the stability regime of the boundary layer and the surface roughness.

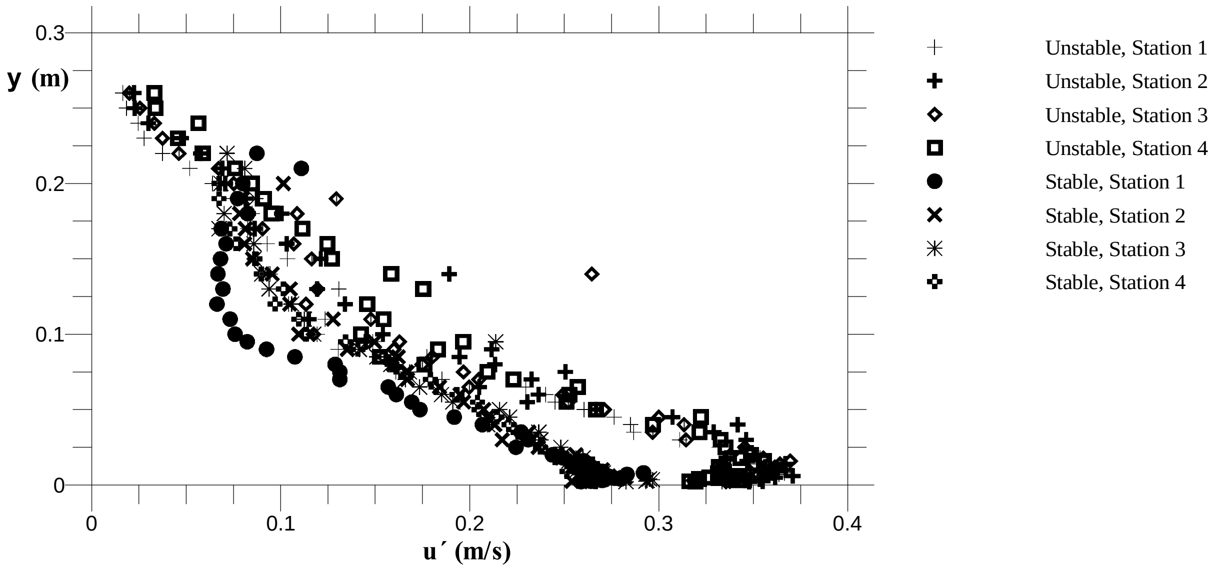

Figure 8. Velocity fluctuations dimensional coordinates.

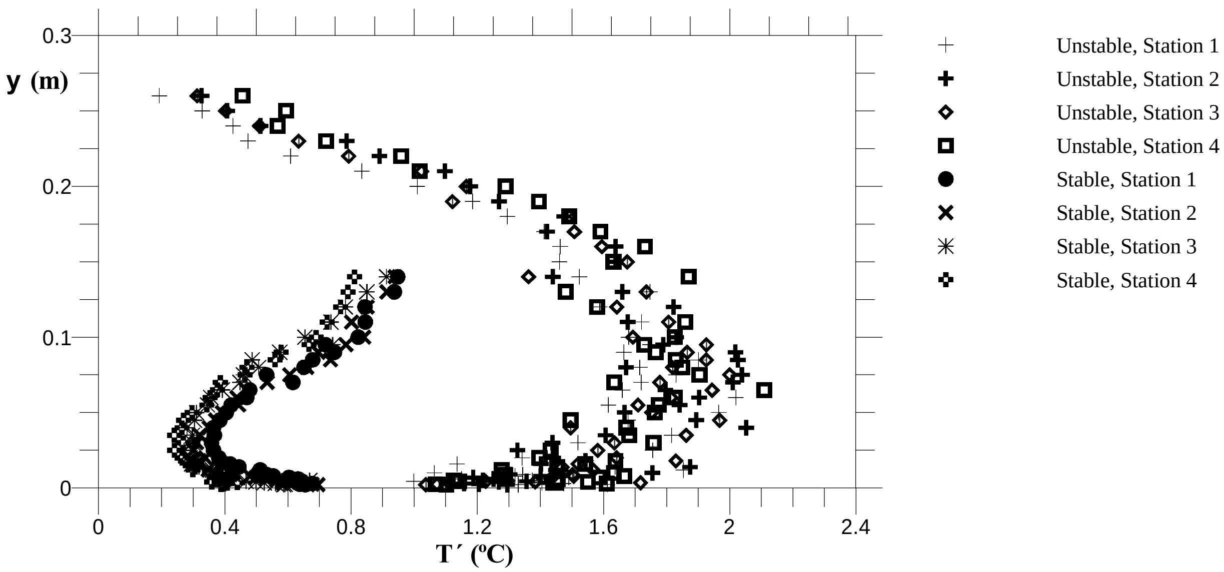

Figure 9. Temperature fluctuations dimensional coordinates.

6. Conclusion

In this work we have performed an experimental analysis of turbulent flows over rough surface under stable and unstable density stratification conditions. This preliminary study has clearly pointed to two main lines of investigation that must be pursued in the future: 1) to examine the failure in the Perry and Joubert procedure to evaluate ε under unstable flow conditions, 2) to examine the physical mechanisms that have led the stable flow to develop a point of minimum temperature fluctuation near the wall. In addition, an study of the suitability of Businger's relations to describe density stratified flows will be made.

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