IX CONGRESSO BRASILEIRO DE
ENGENHARIA E CIÊNCIAS TÉRMICAS

9th BRAZILIAN CONGRESS OF THERMAL
ENGINEERING AND SCIENCES

Paper CIT02-0209

A Comparison Between Wind Tunnel Simulations and Field Measurements of Atmospheric Boundary Layers.

Marcio Cataldi
Mechanical Engineering Program (PEM/COPPE/UFRJ), Federal University of Rio de Janeiro, C.P. 68503, 21945-970 - Rio de Janeiro - Brazil.
mcataldi@serv.com.ufrj.br

Juliana B. R. Loureiro
Mechanical Engineering Department (DEM/EE/UFRJ), Federal University of Rio de Janeiro, C.P. 68503, 21945-970 - Rio de Janeiro - Brazil.
jbrloureiro@serv.com.ufrj.br

Luiz Cláudio G. Pimentel
Meteorology Department (IGEO/UFRJ), Federal University of Rio de Janeiro, 21945-970 - Rio de Janeiro - Brazil.
pimentel@lttc.coppe.ufrj.br

Atila P. Silva Freire
Mechanical Engineering Program (PEM/COPPE/UFRJ), Federal University of Rio de Janeiro, C.P. 68503, 21945-970 - Rio de Janeiro - Brazil.
atila@serv.com.ufrj.br

Abstract. *The objective of this work is to develop, in a wind tunnel environment, boundary layers with different states of development that simulate the structure present in the atmospheric boundary layer. The work analyses the dynamic and thermal characteristics of different types of thick, artificially generated, turbulent boundary layers. The thermal boundary layer is obtained by two methods: wall surface heating and main flow heating. The wall surface heating, made through eletrical resistances, can furnish an increase in wall temperature of up to 100 °C above the ambient temperature and can be applied over a 6000 mm long surface with a controled variation of 2 °C. The main flow heating is obtained by forcing the flow pass through a curtain of copper strings whose elements can the heated individually. The main flow can be heated up to 50 °C. The whole system can then be used to produce, unstable, neutral and stable boundary layers. The parameters of the thermal boundary layer are qualified through: growth, structure, equilibrium, turbulent transport of heat and energy spectrum. The paper describes in detail the experimental arrangement, including the geometry of the wind tunnel and of the instrumentation.*

Keywords: *Stratification, atmospheric boundary layer, wind tunnel.*

1. Introduction

Stratified atmospheric flows have been the subject of extensive research. Because over large lapses of time the temperature in the atmosphere changes abruptly with height, be it daytime or nighttime, air parcels displaced vertically will experience net buoyancy forces resulting in persistent stratified flow states. Thus, if reliable numerical weather prediction and circulation models are to be proposed, the dynamics of stratified flows must be well understood. Of particular interest in this subject is the account of small scale phenomena on the flow features.

Unfortunately, the direct observation of atmospheric flows is a very difficult and costly affair. To observe natural flows, the common practice is to use instruments attached to fixed towers or fitted to aircrafts, balloons or kites. In all cases the difficulties are many and the costs high. An alternative approach is to resort to laboratory observation. The advantages of a controlled laboratory study are many. However, extreme care must be taken to ensure that data obtained in wind tunnels show good similarity with corresponding atmospheric data. Since the number of parameters that influence the atmospheric boundary layer is large this is a very difficult task. Typical parameters are the cycle of solar heating of the ground, mesoescala phenomena and ground orography.

The purpose of this article is to present the results of a series of stratified wind tunnel experiments carried out at PEM/COPPE/UFRJ. The experiments aimed at producing stable, neutral and unstable flows in a short wind tunnel. To generate boundary layers that satisfied the requirements for geometric, dynamic and thermal similarity with the atmospheric boundary layer several special measures were taken. Data validation was made by comparison of results obtained in the present facilities with data taken from other laboratories and the field.

The present work is part of a larger effort whose aims are: i) to investigate methods of simulating stable, neutral and unstable boundary layers in a wind tunnel, ii) to study the effects of rough surfaces on stratified boundary layers, and iii) to study the effects of orography on stratified boundary layers.

The paper shows how the boundary layer that is formed over the floor of the wind tunnel is controlled by heating the floor and the incoming air through eletrical resistances. The resistances can furnish an increase in floor temperature of up to 100^oC above ambient temperature and can be applied over a 6000 mm long surface with a controled variation of $\pm 5^oC$. The incoming air is heated by forcing the flow through a set of 10 electrical heating elements which can be operated individually. The system can then be used to produce unstable, neutral and stable boundary layers. Despite the 6000 mm heating length, only 2000 mm will be used in this work; that is because we are particularly interested in producing stratified flows over a short length.

To create a thick boundary layer in the wind tunnel we resort to the method developed by Barbosa et al.(2000). In their work, these authors show how a combination of spires and bars can be used to generate boundary layers as thick as 28 cm over lenghts as short as 5 meters. The experimental assessment of the thickening device was carried out considering the integral properties of the flow, skin-friction, mean velocity profiles in inner and outer coordinates and turbulence.

A short revision of the conditions in which boundary layer similarity is achieved is also presented here.

2. Similarity Conditions

The general requirements for similarity of flows are dictated by the equations of motion – conservation of mass, momentum and energy. To simulate the atmospheric boundary layer in a wind tunnel the large number of dimensionless groups that would have to be matched to assure exact similarity seems to render the problem impossible to solve since, in principle, all conditions would have to be satisfied simultaneously by the model and some are incompatible or even conflicting. Thus, only approximate similarity can be achieved in a laboratory experiment; the result is that small scale experiments must be designed to represent accurately the characteristics of motion which are of most important for the desired application.

Following the procedure of Cermak(1971) we take as the basic physical model a boundary layer developed over the floor of a wind tunnel test section in which vertical temperature gradients are controlled by heating. The effects of radiation heat transfer and phase changes of water in the atmosphere will not be accounted for in the present analysis. Also, extreme meteorological events which give rise to local singular motions are not considered here.

The requirements for geometric, dynamic and thermal similarity can be obtained by direct inspection of the equations of motion. The equation of continuity remains invariant when transformed to dimensionless form provided a same characteristic length is taken for the vertical and horizontal directions.

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho U_i}{\partial x_i} = 0. \tag{2}$$

The momentum equation can be cast as

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} + \frac{1}{R_o} 2\epsilon_{ijk}\Omega_j U_k = -\frac{\partial P}{\partial x_i} - R_i(\Delta T) g \delta_{i3} + \frac{1}{R_e}\frac{\partial^2 U_i}{\partial x_k \partial x_k} + \frac{\partial}{\partial x_j}\langle -u_i' u_j' \rangle, \tag{3}$$

by scaling all variables in relation to the reference quantities L_0, U_0, Ω_0, ρ_0, ΔT_0 and g_0. Equation 3 is the time averaged Navier-Stokes equation where all variables represent a mean value. The fluctuating variables are indicated by a dash and the brackets $\langle\ \rangle$ indicate an average operation. U_i stands for the velocity component in the x_i direction, p for the pressure, g for the gravitational acceleration, ΔT for the temperature deviation, ν for the kinematic viscosity, Ω for earth's angular velocity and ϵ_{ijk} for the permutation tensor.

The effects of temperature stratification on the velocity field have been accounted for by Boussinesq approximation; this limits equation 3 to situations where $\Delta T << T_0$ and implies that p is the departure of the mean pressure from the hydrostatic pressure for an atmosphere of density ρ_0.

Equation 3 leads to the conclusion that complete dynamic similarity depends on the following dimensionless groups:

Rossby number;	$R_o = U_0/L_0\Omega_0$,
Reynolds number;	$R_e = U_0 L_0/\nu_0$,
Richardson number;	$R_i = [(\Delta T_0)T_0](L_0/U_0^2)g_0$.

When no rotation is imposed on the wind tunnel about a vertical axis, the Rossby number for the wind tunnel will be smaller than that for the atmosphere by a factor of approximatedly 10^{-3} (the length scale). This is a serious limitation to laboratory simulation of atmospheric flows for we know that at geostrophic heights, when the pressure forces and the Coriolis forces reach equilibrium, wind direction varies by an angle of 10^o to 30^o from ground level. Some authors have removed this limitation through the introduction of a cross flow through porous walls of a stationary wind tunnel or by use of a large rotating flow chamber (Cermak(1971)); this has incurred very high costs and great operational difficulties. Rossby number similarity will, hence, be excluded from the present analysis. This limits our representation of the atmospheric boundary layer to the first 150 meters from ground level. This portion of the atmospheric boundary layer is referred to in literature as the atmospheric surface layer.

The Reynolds number for the wind tunnel will also be 10^{-3} smaller than that for the atmosphere. Reynolds number similarity is therefore not achievable. This fact, however, does not complicate our attempt at modelling the atmospehre for we know that for flows over rough surfaces the near wall flow becomes independent of viscosity, being a function of the roughness scale. Since all natural surfaces are rough, the flow structure related to momentum transfer will be equal provided the roughness lengths are appropriately scaled down.

The bulk Richardson number that is typical of the atmosphere, -1 $< R_i <$ 1, can be obtained in a wind tunnel.

Thermal similarity is studied through the enegy equation.

$$\frac{\partial T}{\partial t} + U_i \frac{\partial T}{\partial x_i} = \frac{1}{R_e P_r} \frac{\partial^2 T}{\partial x_k \partial x_k} + \frac{\partial}{\partial x_i} \langle -\theta_i' u_j' \rangle + \frac{E_c}{R_e} \Phi. \tag{4}$$

Equation 4 adds two dimensionless groups to our problem:

Prandtl number; $P_r = \nu_0/(k_0/\rho_0 C_{p0})$,
Eckert number; $E_c = U_0^2/C_{p0}(\Delta T)_0$.

If air is used as the working fluid in the wind tunnel, Prandtl number similarity is immediately achieved. The influence of Eckert number on similarity considerations is not relevant until the flow approaches the speed of sound; this requirement is therefore relaxed.

In addition to equality of the dimensionless groups, requirements assuring that the boundary conditions and the approach-flow characteristics are similar for the wind tunnel and the atmosphere must be observed.

Similarity of surface conditions is characterized by the following factors:

1. Surface roughness,
2. topografic relief,
3. surface temperature distribution.

The approach-flow is characterized by:

1. Upstream distribution of mean and turbulent velocities,
2. upstream distribution of mean and turbulent temperatures,
3. longitudinal pressure gradient.

3. Wind Tunnel Design

The size of the wind tunnel test section will determine the model length scale ratio (LSR). Many wind tunnels are designed to represent the first 500 m of the atmosphere. For these, a scale ratio of 1:500 is used so that one meter thick boundary layers will have to be produced in the laboratory. Boundary layers with this thickness require very long test sections to be achieved resulting in large experimental instalations. Meteorological wind tunnels can have a working cross section as large as 7x12 meters with a total section length of 40 meters (Monash University). However, many other tunnels present much short working cross sections varying from 0.5x0.5 m to 3x4 m. Design recommendations have been advanced by several authors, Cermak(1971, 1975, 1981), Poreh et al.(1991), Meroney and Melbourne(1992), Grainger and Meroney(1994), Ohya et al.(1994) and Fedorovich et al.(1996). All authors agree that an atmospheric wind tunnel should ideally have a working section longer than 10 meters. Indeed, Cermak(1975) has shown that only after 10 meters from the test section's entrance the turbulent boundary layer becomes fully developed. This is in agreement with the findings of other authors. Furthermore, Poreh et al.(1991) have shown that the minimum desired wind tunnel dimension for diffusion experiments is 10 meters.

The general features of typical atmospheric wind tunnels are shown in Table 1. To construct this table, data was taken from the following facilities: Cornell University, Ithaca, USA, Yoon(1990); Colorado State University, Fluid Dynamics and Diffusion Laboratory, USA, Cermak(1975); Ecole Centrale de Lyon, Ecully, France,

Table 1: Atmospheric wind tunnel features.

	C. S.	L.	U	dT/dz	δ
Cornell	0.91x0.91	9.14	2.8-4.2	55	
Colorado	1.8x1.8	24	0.1 to 30	114	1.4
ECL	1.2x1	10	1 to 20		0.4
Karlsruhe	1.5x1.5	10	0.5-8	120	0.75
Kyushu	1.5x1.2	13.5	0.2-2	125	
Monash	10x5	40	0.5		0.3
MHI	2.5x1	10	0.4-1.5		
NIES	3x2.4	24	0.2-10	25	1

Table 2: Wind tunnel instrumentation.

	HWA	LDA	CWT	Th	MWT	P_W
Cornell	Yes		Yes			
Colorado	Yes	Yes	Yes	Yes	205	
ECL	Yes		Yes		100	
Karlsruhe		Yes	Yes	Yes		32
Kyushu				Yes	4-80	50
Monash	Yes		Yes			9
MHI	Yes	Yes	Yes	Yes	0-100	7
NIES	Yes		Yes	Yes	7-112	

Reynolds(1978); Institut für Hydrologie und Wasserwirtschaft, Karlsruhe, Germany, Rau(1991); Research Institut for Applied Mechanics, Kyushu University, Kasuga, Japan, Ohya(1996); Dept.Mechanical Engineering, Monash University, Australia, Grainger(1994); Mitsubishi Heavy Industries, Nagasaki, Japan, Ohba(1990); National Institute for Environmental Studies, Ibaraki, Japan, Ogawa(1981).

The instrumentation used in these tunnels is reviewed in Table 2.

The data in Tables 1 and 2 give us some criteria as to what should be the operating range of an atmospheric wind tunnel. At this point we recognize that by using vortice generators and roughness elements, a large range of integral scales can be introduced into the boundary layer. In fact, a previous study by Barbosa et al.(2000) showed how a simple combination of cylindrical rods and rectangular bars can be used to produce artificial boundary layers with thicknesses up to 27 cm in a 5 m short wind tunnel test section. The experimental assessment of the generators was carried out by considering the integral properties of the flow, skin-friction, mean velocity profiles in inner and outer coordinates and turbulence.

Because of the very high cost involved in designing, constructing and operating a large atmospheric wind tunnel, we have decided at COPPE/UFRJ to construct a small pilot tunnel. The tunnel, if possible, should be capable of reproducing stable, neutral and unstable flows.

After careful consideration, a wind tunnel with the following characteristics was constructed:

- 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: 5 kW m^2.
- Lenght of wall heating section: 6 m.
- Wall temperature: variable from 21 to $100^o C$.
- Number of resistences used to heat the incoming air: 10.
- Resistances capacity: 2 kW.

Table 3: Atmospheric boundary layer characteristics (Driffield Power Station, Australia).

Inversion Height, zi:	1000 m
Mean Velocity:	4 m/s
Mean Temperature:	20 ^{o}C
Heat Flux:	400 W/m^2

- Vortice generators: rods with 1/8" diameter and 16 mm lenght spaced by 10 mm. One or two trailing transversal trips were also used.

A general view of the wind tunnel can be seen in Figure 1 together with a drawing illustrating the positioning of the heating elements.

Figure 1. General view of wind tunnel and the heating elements.

Two-component velocity measurements and temperature measurements were obtained using thermal anemometry. The output voltage of a constant-temperature hot-wire anemometer can be represented, as recommended by Brunn(1987), by

$$E^2 = A(T) + B(T)U^{0.45} \tag{5}$$

where T is the air temperature and U the flow speed.

The appropriate functional behaviour of $A(T)$ and of $B(T)$ was determined by calibrations performed in a specially designed wind tunnel of 300x300 mm cross section. Typically, $A(T)$ and $B(T)$ were shown to have a linear behaviour.

For two-component velocity measurements a Dantec 55P61 x-wire was used together with a micro-thermocouple to obtain the desired temperature correction. For one-component velocity and temperature measurements, a Dantec 55P76 sensor was used.

For the tunnel instrumentation, the following instruments were available: 6 constant temperature anemometer units, 2 constant current anemometer units, 1 pulsed-wire anemometer unit, a range of hotwire probes and supports, 16 thermocouples, 5 pitot tubes, one micromanometer, one inclined manometer with 18 tubes, an automatic traversing gear system (0.02 mm sensitivity), all necesary support equipment (oscilloscopes, microcomputers, multimeters).

4. Wind Tunnel Performance

The results taken from the wind tunnel constructed at COPPE/UFRJ will be compared here with some real flow data and data of other authors. Typical atmospheric conditions are shown in Table 3.

The global flow parameters are shown in Table 4 where G stands for the Clauser factor, u_τ for the skin-friction velocity, δ for the boundary layer thickness, δ_2 for the momentum thickness and n for the exponent in the power law.

We clearly see that both the naturally and the artificially generated boundary layers are in equilibrium condition under the neutral state. All the other parameters are also very much within the expected trends.

The Monin-Obuckhov characteristic length can be calculated (Kaimal and Finnigan(1994)) according to

$$L = \frac{u_\tau^3 \overline{\theta_v}}{\kappa g (q'/\rho c_p)}, \tag{6}$$

Table 4: Global flow parameters.

	Stable		Neutral		Convective	
	ABL	WT	ABL	WT	ABL	WT
G	5.09	6.77	7.45	7.71	6.27	8.98
u_τ	0.09	0.06	0.08	0.07	0.10	0.12
δ	0.05	0.11	0.05	0.14	0.05	0.11
δ_2	0.004	0.011	0.007	0.018	0.005	0.013
n	0.2	0.21	0.2	0.22	0.25	0.35

where $\overline{\theta_v}$ denotes the ambient temperature or the mean temperature above the boundary layer; κ is von Karman's constant and q' the heat flux at the wall. All other quantities take on their classical meaning.

The estimated value of q' was 314 W/m^2; then, it follows that for the naturally developed boundary layer L = -0.59 m, whereas for the artificially thickned boundary layer L = -0.60 m.

The Richardson number was evaluated according to:

$$R_i = \frac{g(T_H - T_B)(H - B)}{T(U_H - U_B)}, \tag{7}$$

where the subscripts H and B indicate the position in which the measurements are taken: H indicates the higher position of the probe, B indicates the lower position.

For 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.

$$u(z) = \frac{u_\tau}{\kappa}\Big(\ln\frac{z}{z_0} + \gamma_m \frac{z}{L}\Big), \tag{8}$$

$$T(z) = T(z_0) + \alpha_h \frac{t_\tau}{\kappa}\Big(\ln\frac{z}{z_0} + \gamma_h \frac{z}{L}\Big), \tag{9}$$

where u_τ is the friction velocity, z_0 is the roughness length, $\alpha_h = 0.74$ (Businger et al(1974)) or 1.0 (Dyer(1974)), t_τ is the friction temperature, $\gamma_h = 4.7$ (Businger et al(1974)) or 5.0 (Dyer(1974)).

b) Unstable flow.

$$u(z) = \frac{u_\tau}{\kappa}\Big(\ln\frac{z}{z_0} - \psi_m \frac{z}{L}\Big), \tag{10}$$

$$T(z) = T(z_0) + \alpha_h \frac{t_\tau}{\kappa}\Big(\ln\frac{z}{z_0} + \psi_h \frac{z}{L}\Big), \tag{11}$$

where

$$\psi_m = 2\ln\frac{1+x}{2} + \ln\frac{1+x^2}{2} - 2\tan^{-1}x + \frac{x}{2}, \tag{12}$$

with

$$x = (1 - \beta_m \frac{z}{L})^2 \tag{13}$$

and $\beta_m = 9$ (Businger et al.(1971)) or 16 (Dyer(1974)).

When the boundary layer is divided into two portions, an inner and an outer layer, the Richardson number can be evaluated using Eq.(7). Table 5 compares the results found at COPPE/UFRJ with the results of other wind tunnels and the atmospheric boundary layer.

The following figures show the experimental results in scattergraph form and theoretical results in line graph format. Measurements were taken at four different points from the start of the test section, at 2.3m (station 1), 2.5m (station 2), 2.7m (station 3) and 2.9m (station 4).

Figure 2 shows the streamwise variation of the temperature; it shows clearly that in the first two stations the temperature profiles have not yet accommodated to a logarithmic form. In fact, even the last two profiles

Table 5: Richardson number for inner and outer layers.

	Stable	Neutral	Unstable
ABL	0.022	0	-0.021
Grainer and Meroney	0.004D	—	—
Ogawa et al.	—	—	-0.29
Layer 1, Artificial	0.001	0.0002	-0.037
Layer 1, Natural	0.001	0.0002	-0.036
Layer 2, Artificial	—	0	-0.005
Layer 2, Natural	0.001	0.0002	-0.036
Artificially thickened	0.004	0.0001	-0.027
Naturally thickened	0.022	0	-0.026

cannot be considred in a equilibrium state. That is indication that for a quality profile the wind tunnel has to be further alongated.

The mean velocity profiles for naturally developed and artificially developed stable boundary layers are shown in Figure 3 in linear and logarithmic coordinates respectively. The temperature profile also in linear and logarithmic coordinates are shown in Figure 4 respectively. The Monin-Obukov length and the Richardson number are shown in Figures 5. The temperature streamwise variation for the unstable case is shown in Figure 6. All these graphs are repeated for the unstable condition in Figures 7 through 9. The mean velocity and temperature profiles shown here refer to the values taken at the station 4.

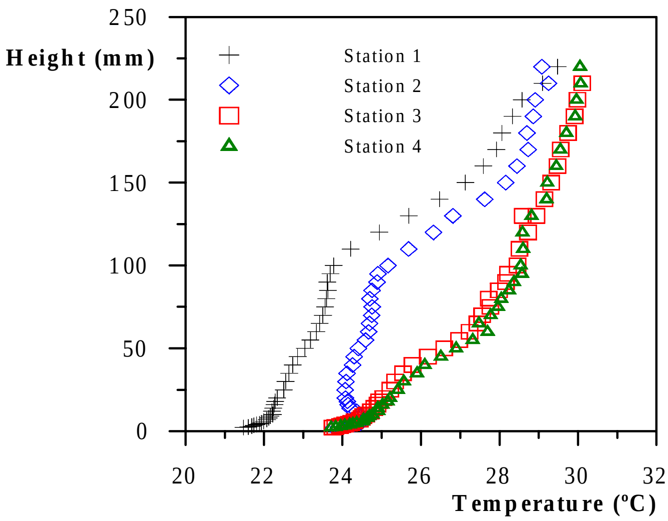

Figure 2. Temperature profiles in dimensional coordiantes for several streamwise stations; stable conditions.

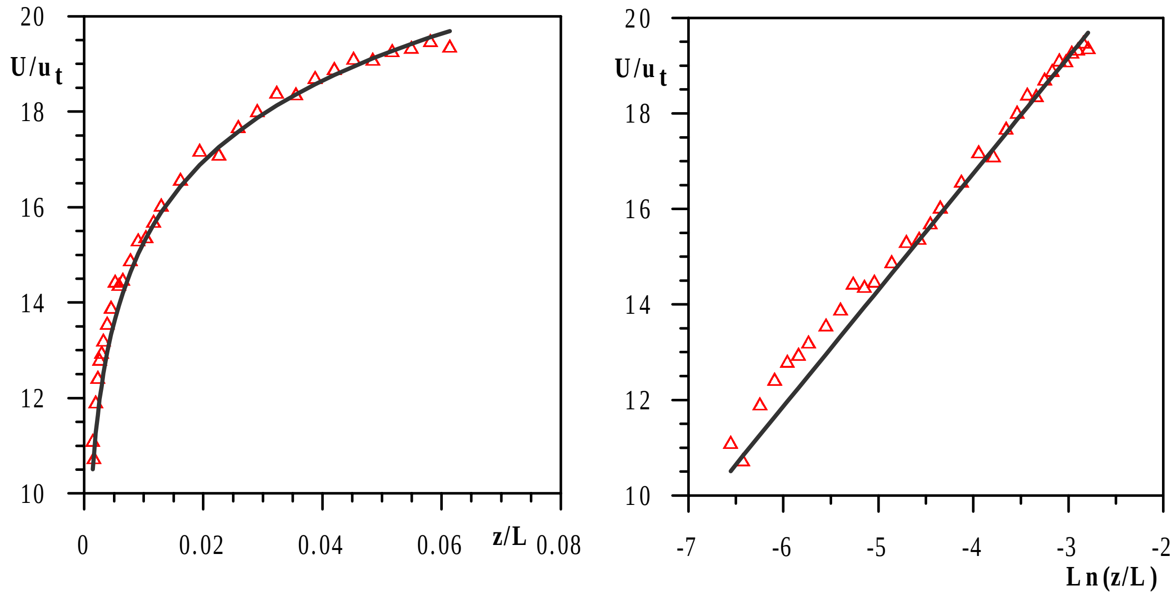

Figure 3. Velocity profiles in linear and logarithmic scales; stable conditions.

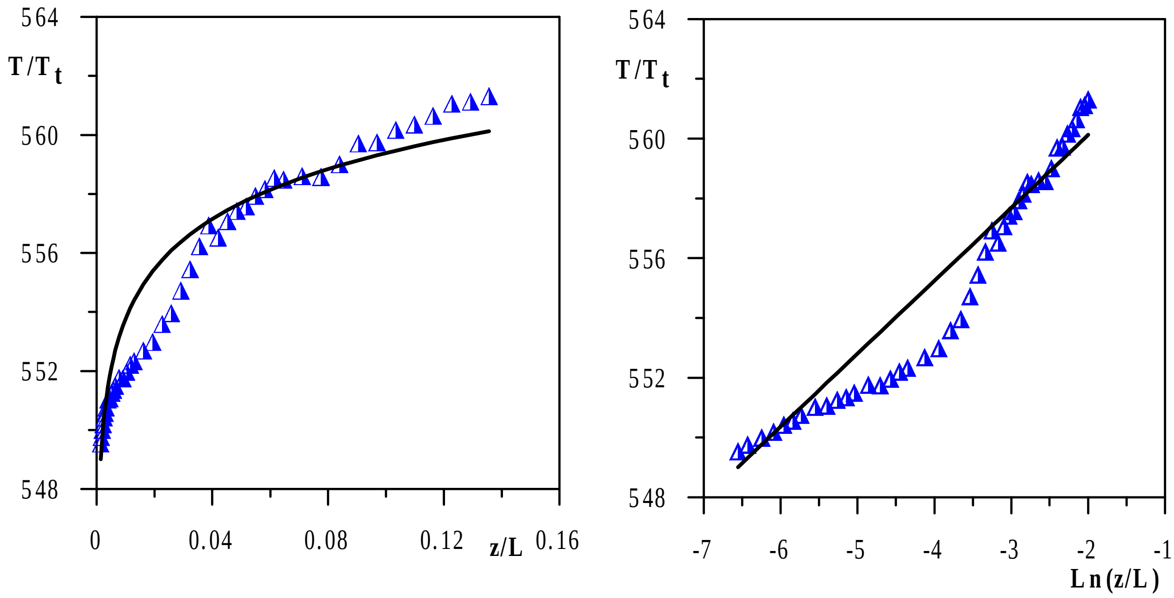

Figure 4. Temperature profiles in linear and logarithmic scales; stable conditions.

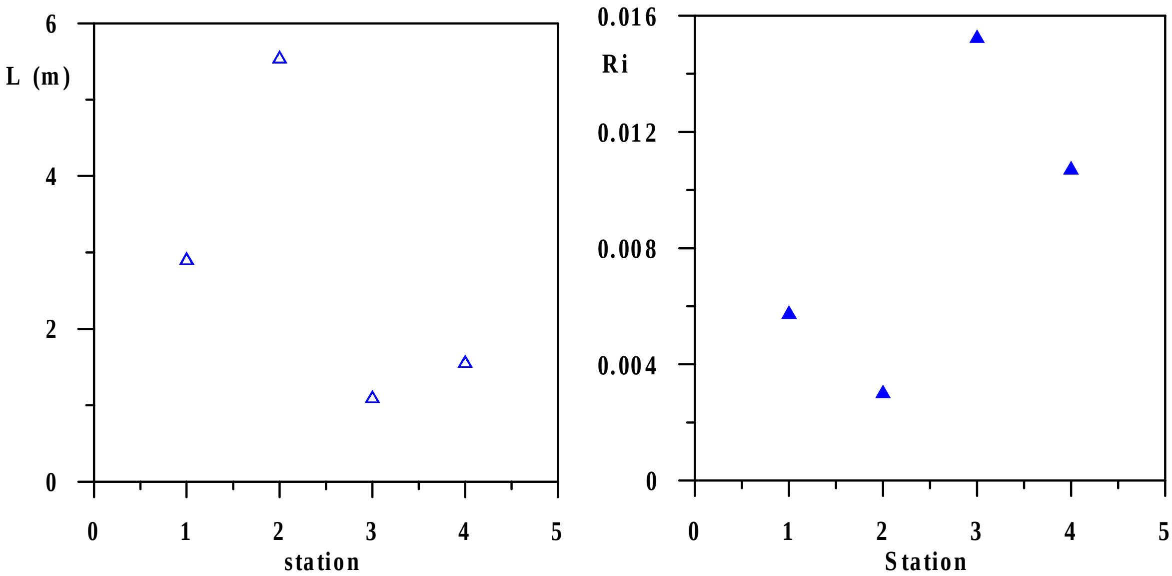

Figure 5. Monin-Obuckhov length and Richardson number; stable conditions.

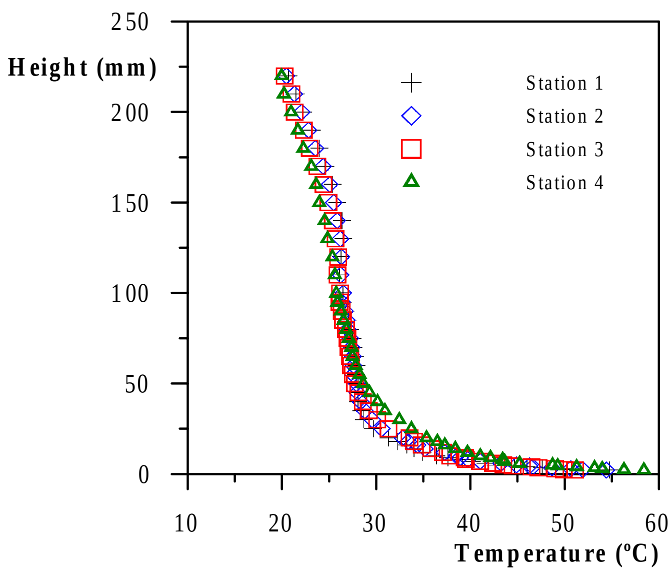

Figure 6. Temperature profiles in dimensional coordiantes for several streamwise stations; unstable conditions.

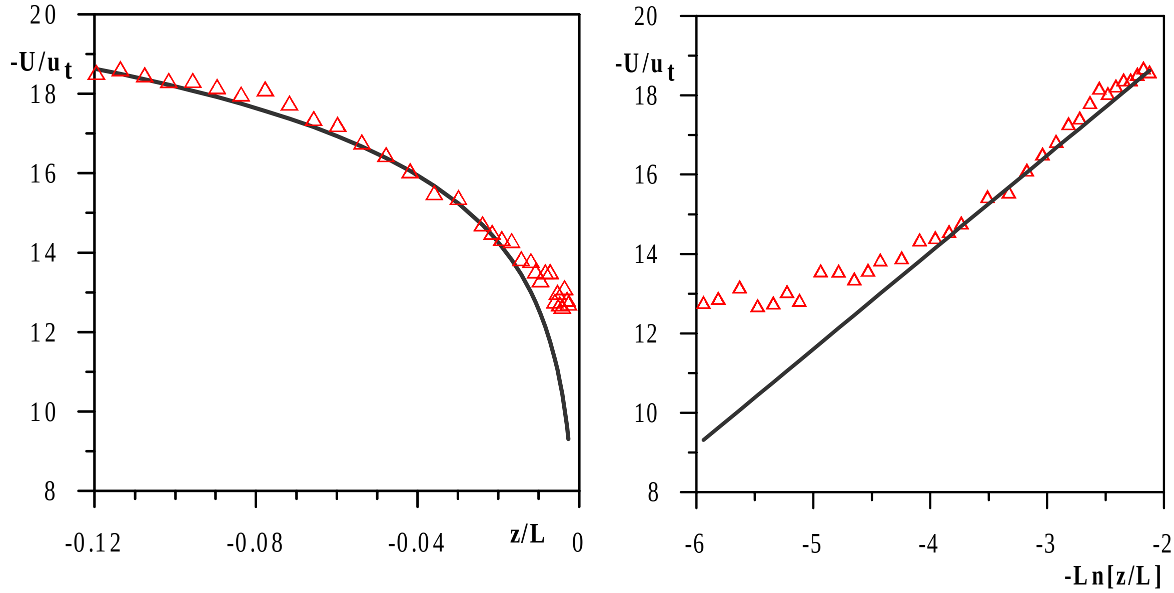

Figure 7. Velocity profiles in linear and logarithmic scales; unstable conditions.

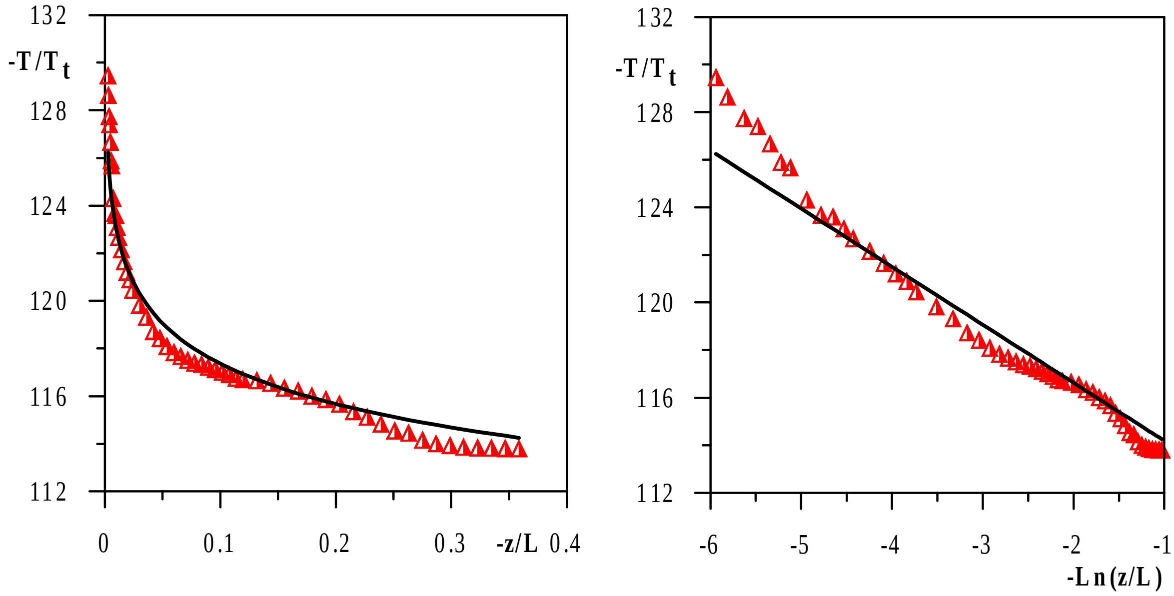

Figure 8. Temperature profiles in linear and logarithmic scales; unstable conditions.

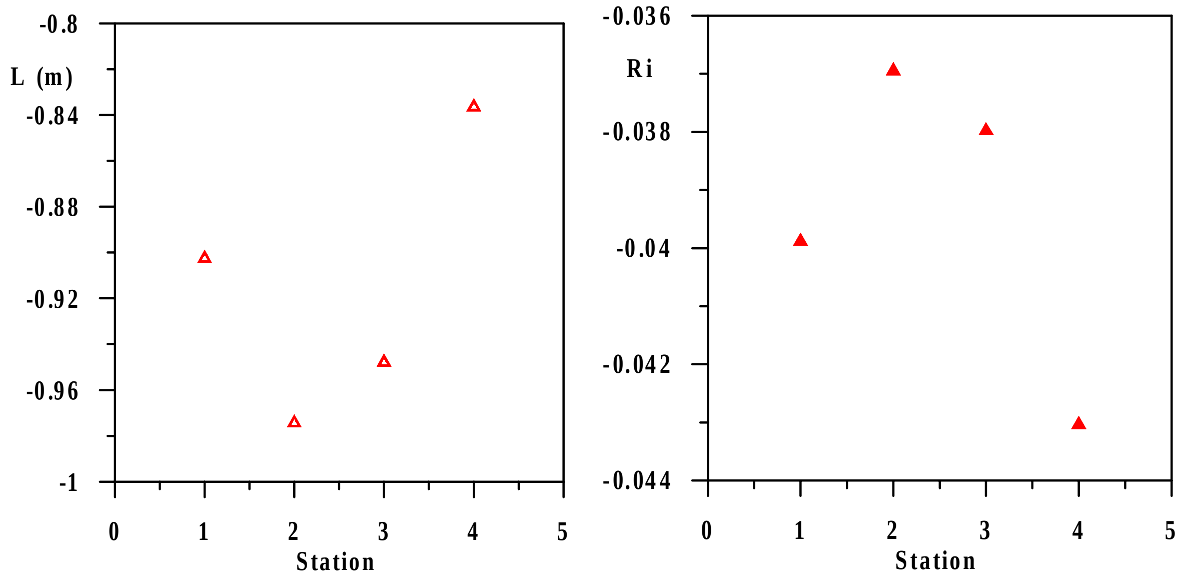

Figure 9. Monin-Obukov length and Richardson number; unstable conditions.

The results show that distinct characteristics were obtained for all flow conditions. The logarithmic profile is strictly valid only for the neutral boundary layer. However, we have shown that for the stable and unstable flow conditions the departures from the logarithmic profile can be adequatedely represented by the Businger-Dyer relations. The skin-friction coefficient and the Stanton number have been estimated considering these relations valid.

The law of the wake has been reasonably well discriminated for all situations.

5. Conclusion

The present work has reported the recent progress made at COPPE/UFRJ to construct a pilot wind tunnel which can generate boundary layers with characteristics close to those presented by an atmospheric flow.

The values found for the Richardson number and for the Monin-Obuckhov length shows that a low degree of stability was achieved in the simulation of stable boundary layers, and a moderate degree of instability was found in the simulation of unstable boundary layers. The unstable case's mean temperature dimensional profiles collapsed, while the stable case's did not.

In most cases, the profiles showed a good degree of similarity to the theoretical profiles, except for the stable boundary layer simulation's temperature profiles, which demonstrates that this kind of simulation requires a greater length in the tunnel's test section.

Results for stable, neutral and unstable flows were presented. In general, very satisfactory results were achieved. The velocity and temperature profiles were shown to adhere well to the atmospheric boundary layer features, knowing that in the theoretical solutions the empiric constants used were obtained from Dyer(1974) in atmospheric boundary layer experiments.

Acknowledgements. The present work was been financially supported by the CNPq through grant No 350183/93-7. MC and JBRL are also grateful to CNPq for the award of research scholarships.

6. References

Barbosa, P. H., Cataldi, M. and Silva Freire, A. P.; "Wind tunnel simulation of atmospheric boundary layer flows", 7th ENCIT, Porto Alegre, 2000

Businger, J.A., Wyngaard, J.C., Izuni, Y. and Bradley, E.F.; "Flux-profile relationships in the atmospheric surface layer", J. Atmos. Sci., Vol. 28, 181-189, 1971.

Cermak, J.E., "Laboratory Simulation of the Atmospheric Boundary Layer", AIAA J., Vol. 9, 1746-1753, 1971.

Cermak, J.E., "Application of Fluid Mechanics to Wind Engineering – A Freeman Scholar Lecture", J. Fluids Engng., Vol. 97, 9-38, 1975.

Cermak, J.E., "Wind Tunnel Design for Physical Modeling of Atmospheric Boundary Layers", Proceedings of ASCE, Vol. 107, 623-641, 1981.

Dyer, A.J., "A Review of Flux-Profile Relationships", Bound.-Layer Meteor., Vol. 7, 363-372, 1974.

Fedorovich, E., Kaiser, R., Rau, M. and Plate, E.,"Wind Tunnel Study of Turbulent Flow Structure in the Convective Boundary Layer Capped by a Temperature Inversion", J. Atmosph. Sciences, Vol. 53, 1273-1289, 1996.

Grainger, C. and Meroney, R., "Inverted Floor Wind-Tunnel Simulation of Stably Stratified Atmospheric Boundary Layer Flow", Atmosph. Envir., Vol. 28, 1887–1893, 1994.

Kaimal, J. C. e Finnigan, J. J.; Atmospheric boundary layer flow; Oxford University Press, 1994.

Meroney, R.N. and Melbourne, W.H., "Operating ranges of Meteorological Wind Tunnels for the simulation of Convective Boundary Layer(CBL) Phenomena", Boundary-Layer Meteor., Vol. 61, 145–174, 1992.

Ohba, R., Ukegushi, N., Kakishima, S e Lamb, B.; Wind tunnel experiment of gas diffusion in stably stratified flow over a complex terrain, Atmospheric Environment, 24A, 1987–2001, 1990.

Ogawa, Y., Diosey, P.G., Uehara, K. and Ueda, H., "A Wind Tunnel for Studying the Effects of Thermal Stratification in the Atmosphere", Atmosph. Envir., Vol. 15, 807–821, 1981.

Ohya, Y., Nakamura, Y. and Ozono, S.,"A Wind Tunnel for Studying Density-Stratified Flows", Atmosph. Envir., Vol. 28, 1895–1900, 1994.

Poreh, M., Rau, M. and Plate, E.J., "Design Considerations for Wind Tunnel Simulations of Diffusion within the Convective Boundary Layer", Atmosph. Envir., Vol. 25A, 1251–1256, 1991.

Rau, M., Bächlin, W. and Plate, E.J., "Detailed Design Features of a New Wind Tunnel for Studying the Effects of Thermal Stratification", Atmosph. Envir., Vol. 25A, 1258–1263, 1991.