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WIND TUNNEL SIMULATION OF CONVECTIVE BOUNDARY LAYER PHENOMENA:
Simulation Criteria and Operating Ranges of Laboratory Facilities

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WIND TUNNEL SIMULATION OF CONVECTIVE BOUNDARY LAYER PHENOMENA

Simulation Criteria and Operating Ranges of Laboratory Facilities

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Abstract:
The operating ranges of meteorological wind tunnels for convective boundary layer (CBL) surface layer simulation are defined in this paper based on a review of the theoretical and practical limitations of the flow phenomena and the facilities available. Wind-tunnel operating ranges are limited by the dimensions of the simulated circulations and of the tunnel itself, the tunnel flow speed and turbulence processes, and the characteristics of the measurement instrumentation.

1. Introduction

Convective boundary layer (CBL) circulations are surface temperature-forced atmospheric circulations observed almost daily over most of the earth's surface. An understanding of the convective boundary layer (CBL) has only begun to emerge from laboratory, field and numerical research in the last thirty years. Recent studies have focused on the characteristics of the large and central mixed layer, but still unresolved are the details of how the various CBL sublayers are linked together. Much of the remaining difficulties relate to the fact that definitive measurements in regions above the meteorological tower heights but below the mixed layer and above the mixed layer within the capping entrainment layer are difficult to acquire.

Much of today's understanding of the CBL has come from convection tank and laboratory studies. Conventional type and size water tank and wind tunnel facilities provided data which were used to interpret the mixed-layer atmospheric physics and to validate analytic and numerical models for plume behavior (Thorpe [29]). Routine engineering investigations of CBL impact on power-plant plumes or other activities of man will be constrained by the inherent limitations of the size and type of simulations used. This paper examines some of the limitations of fluid modeling.

2. Laboratory Simulation of the CBL

Much of the understanding of the CBL has come from convection tank and large eddy simulation (LES) studies. The original work by Willis and Deardorff [31] is now complimented by wind-tunnel measurements taken at Colorado State University (Arya and Plate [1]; Poreh and Cermak [24]), University of Karlsruhe (Poreh, Rau and Plate [26]; Rau, Bachlin and Plate [27]; Fedorovich, Kaiser and Rau [10]; Fedorovich and Kaiser [8]; Kaiser and Fedorovich [9]), and the work at the Atmospheric Research Division, CSIRO Aspendale, Australia, who are using a salt-water analogue to the thermal CBL process to simulate mixing layer phenomena (Hibberd and Sawford [11]).

Thermally stratified wind tunnels currently exist at Colorado State University, USA (2 m x 2 m cross-section, 30 m long) and at the National Institute for Environmental Studies, Japan (2 m x 3 m cross-section, 24 m long). New wind-tunnel facilities specifically designed to study the CBL are under construction or evaluation at the Central Electricity Generating Facility, Leatherhead, UK (1.5 x 3.5 m cross-section, 20 m long), the Ecole Centrale de Lyon, France (2 x 3.7 m cross-section, 15 m long), Karlsruhe University, BRD (0.5 x 1 m cross-section, 4 m long), and the very ambitious facility at Monash University, Australia (5 m x 10 m cross-section, 40 m long).

2.1. WATER-TANK EXPERIMENTS

Laboratory experiments in water tanks have contributed substantially to a better understanding of convectively mixed layers. Experiments with such facilities continue to contribute important information about the mixed layer and its rates of growth. Visualization experiments performed with laser sheets and chemically fluorescing plumes yields detailed information about the mixing characteristics of buoyant plumes in the CBL. These studies clearly demonstrate that the process is non-Gaussian.

Small size limits the spatial resolution characteristics of most water tank simulation of the CBL. Typical mixed layer depths examined are from 0.1 to 0.5 m deep; hence, the equivalent atmospheric surface layer regions are below 1 cm, and the stability length, L, may be at most of the order of millimeters. It is unlikely then that CBL water tank measurements will contribute substantially to a better understanding of the atmospheric surface layer (ASL) where the three-sublayers reside.

Deeper entrainment layers may be produced in larger water tank facilities. For example the Stratified Mixing Facility at Colorado State University consists of a 2 m deep, 10 m long tank provided with thick side wall insulation, floor heating, recirculation pumps, a salt water filling system, visualization windows, and temperature and concentration measurement instrumentation.

2.2. WIND-TUNNEL EXPERIMENTS

Deardorff [7] showed for the CBL that when $-z_i/L_{mo} > 10$ (Note: Arya [2] suggests > 5), then turbulence scales with the mixing layer depth, z_i, and the convective velocity, w_*. Characteristic distributions of temperature, T, velocity, U, and heat flux, $<wt>$, are sketched in Figure 1. Time is expected to scale as tw_*/z_i, vertical distance should scale as z/z_i, horizontal distance as $xw_*/(z_i U_m)$, and concentration as $Cz_i^2 U_m/Q_s$ or $C_I z_i U_m/Q_s$ Assuming undistorted vertical and horizontal scales, this means one must maintain model and prototype w_*/U_m equivalent.

Once the mixing layer depth and convective velocity scales are stipulated for the laboratory experiment, it is also necessary that the rate of mixing layer growth $(dz_i/dt)/w_*$ be similar. Unfortunately, for convenient model velocities, eg., $U_m \approx 1$ to 2 m/s, very large surface heat fluxes may be required, eg., 200 to 15,000 watts/m^2, and intense stable temperature gradients at the top of the mixing layer, eg. $dT/dz \approx 50$ to 2000 °C/m. An alternative approach to the creation of an elevated inversion which might be adequate is to use the upper wind-tunnel roof as the effective inversion height, z_i. The validity of this approach must be examined carefully, however, since a downward flux of heat due to interfacial entrainment plays an important role in many mixed layer characteristics.

3. Wind-tunnel Operating Range for CBL Simulations

Meteorological wind tunnels are, in effect, analog computers with `near-infinitesimal' resolution and `near-infinite' memory (Snyder [28]). They employ real fluids, not mathematical models of fluids, and produce inherently viscous, turbulent, nonhydrostatic, non-Boussinesq, and compressible flows with no-slip boundary conditions. However, flows in scaled physical models are also only partially similar and cannot at present include all processes present in the atmosphere such as Coriolis acceleration, exchange of energy by radiation, conduction into the soil, and phase changes of water.

Simulation of atmospheric motions by wind-tunnel flows has occurred for almost 100 years since Professor LeCour constructed a wind-mill test facility in Askov, Denmark, in 1895 and Gustaf Eifel designed his exhibition tower in 1889. Background reviews about laboratory simulation were prepared by Cermak [4], Davenport and Isyumov [6] and Melbourne [12, 13]. Meroney [15, 18] considered the simulation of complex terrain and valley drainage situations. Snyder [28] suggested similarity criteria for the study of air-pollution meteorology in near neutral situations. Meroney [17] extended the discussion to the simulation of dense-gas plumes in the surface layer. Meroney et al. [19] and Avissar et al. [3] proposed simulation criteria and operating ranges for the simulation of sea and land breezes.

3.1. GENERAL SIMILARITY REQUIREMENTS

During physical model simulations of atmospheric flows, scale-model replicas of observed ground-level buildings and terrain are constructed and inserted into a laboratory flow facility. The flow characteristics and stratifications of the air in the wind tunnel are adjusted to be similar as possible to the atmospheric conditions. Complete equivalence of the laboratory model and atmospheric prototype flow fields requires geometric, kinematic, dynamic, and thermal similarity. In addition, boundary conditions upstream, downstream, at the lower surface, and near the top of the physical model must be similar to those at the corresponding boundaries of the modeled atmospheric domain. These multiple similarity requirements, the characteristics of the wind tunnel and its instrumentation, and the nature of the atmospheric phenomenon to be modeled all help to determine the operating range (OR) for a wind-tunnel simulation.

Similarity characterization of stratified atmospheric flows are summarized by Avissar et al. [3] and Meroney [14]. Specific characterization of CBL phenomena are discussed by Meroney and Melbourne [20], Poreh [23], Poreh, Rau and Plate [26], and Rau, Bachlin and Plate [27]. Equality of the similitude parameters identified by these authors must be supplemented by the requirements that the surface boundary conditions and the approach-flow characteristics also be similar for model and prototype. Boundary-condition similarity requires similar values of

@ Surface roughness,
@ Topographic relief,
@ Surface temperature distribution,
@ Upstream distribution of mean and turbulent velocities,
@ Upstream distribution of mean and turbulent temperatures, including inversion height, and
@ Longitudinal pressure gradient.

If all of the above conditions are met simultaneously, then all scales of motion ranging from the atmospheric microscale to mesoscale could be simulated exactly by the laboratory model. Unfortunately, not all conditions can be satisfied simultaneously by a scaled model since some are incompatible or conflicting; hence, only partial or approximate similarity can be achieved. This suggests that a laboratory model for a particular meteorological situation must be designed to simulate most accurately those scales of motion which are of greatest significance for the application. In the case of a CBL with undistorted horizontal and vertical scales primary parameters of interest will be w_*/U and inversion height, z_i.

3.2. INSTRUMENTATION CHARACTERISTICS

Avissar et al. [3] reviewed wind-tunnel instrumentation characteristics, and they suggested that measurement accuracy was enhanced for model flow speeds of 0.5 m/s and greater. Averaging times and sampling rates may be expected to produce fractional errors of 1, 5 and 10% for averaging times of 400, 16, and 4 seconds, respectively. Conventional sized hot-film instrumentation should produce only a 4% spatial resolution error.

3.3. WIND-TUNNEL CHARACTERISTICS

Simulation of the atmospheric CBL is not only a function of the governing flow physics but also depends on the availability of a suitable simulation facility and its instrumentation. In particular the size of the wind-tunnel test section will determine the smallest model length scale ratio (LSR). Most meteorological tunnels range in size from 0.5 x 0.5 m to those with working cross-sections of 3 x 4 m. An exception is the new environmental wind tunnel at Monash with a cross-section of 5 x 10 m. Density stratification can be induced by use of heat exchangers, injection of heated air, gases of different molecular weight, or latent heat absorption or release during phase change (e.g., Ogawa *et. al.* [22]; Meroney [16]). By using vortex generators, fences, roughness elements, grids, screens or jets, a wide range of turbulence integral scales can be introduced into the tunnel boundary layer. Choice of model surface roughness or stratification permits control of surface turbulence intensity, dimensionless wall shear, and velocity profile shape.

Three tunnels have been chosen to represent the characteristics of such facilities. The meteorological wind tunnel (MWT) at Colorado State University is a large, closed-circuit facility with a 1.8 m high by 1.8 m wide by 24 m long test section. Wind speeds are continuously variable from 0.1 to 30 m s^{-1} and ambient air temperatures can be varied from 5 to 205°C (e.g. Cermak [4]). Ten meters of the upstream floor can be cooled between 1°C and ambient temperature while 12 m of the downstream test-section floor can be heated from 1 to 200°C.

The environmental wind tunnel (EWT) at Monash University is a large, open-circuit facility with a 5-7 m high by 10-12 m wide by 40 m long test section. Wind speeds are continuously variable from 0.1 to 18 ms^{-1} (or to 45 ms^{-1} with cross-section reduced). Ambient air temperatures are drawn into the entrance section, but wall heaters may be inserted to regulate wall temperatures. The wall heaters have a surface heat capacity of 5 kW m^{-2}.

The stratified boundary layer wind tunnel (SBLWT) at Karlsruhe University is a unique configuration closed circuit facility with a 1 m by 1 m by 10 m long test section. Wind speeds are variable from 0.5 to 1 ms^{-1}. Air layers are heated and circulated through ten separate contiguous ducts, and additional surface heating is provided over the test section floor. The wall heaters have a surface heat capacity of 1.5 kW m^{-2}.

Coriolis force considerations also limit the maximum acceptable LSR. Snyder [28] suggests a 5 km maximum cut-off point for horizontal length scales for modeling atmospheric diffusion. Mery *et. al.* [21] suggests a 15 km limit, Ukeguchi *et al.* [30] suggest a 40 to 50 km limit, and Cermak *et al.* [5] proposed a 150 km limit. Given the strong mixing present in CBL situations and time scales of about 3 hours then surface generated stresses should dominate most situations for at least 2 to 5 km.

The following criteria have been identified which limit the MWT, EWT, and SBLWT operational ranges:

TABLE 1: Operational range limitations of typical meteorological tunnels

	Colorado State MWT	Monash EWT	Karlsruhe SBLWT
@ Maximum model inversion height	< 1 m	< 5 m	< 0.5 m
@ Maximum inversion strength	< -50°Cm^{-1}	< -50°Cm^{-1}	< - 100° Cm^{-1}
@ Minimum model inversion height	0	0	0
@ Maximum model blockage	< 5 %	< 5 %	< 5 %
@ Minimum plume Reynolds number	> 300	> 300	< 300
@ Minimum model wind speed	> 0.5 ms^{-1}	> 0.5 ms^{-1}	<5 ms^{-1}
@ Maximum model heat flux	< 5 kWm^{-2}	< 5 kWm^{-2}	<1.5 kWm^{-2}

3.4. WIND-TUNNEL PERFORMANCE ENVELOPES FOR CBL SIMULATIONS

The most severe restrictions on the wind-tunnel operating range or performance envelope result from geometric similarity constraints. For example Deardorff [7] proposed that laboratory conditions should be sought where $-z_i/L_{mo} > 10$ $(z_i/L > 25)$ to simulate the mixed layer. Yet the height of most facilities (1-2 m) would limit the dynamic layer to 2 mm, the dynamic convective layer to 2 cm, and the free convection layer to less than 20 cm. Presuming wind-tunnel facilities with model z_i = 0.5, 1.0 and 2.5 m, respectively, then the various characteristic model depths might be:

TABLE 2. Operating ranges typical meteorological wind tunnels

	Karlsruhe SBLWT	Colorado State MWT	Monash EWT
z_i	0.5 m	1.0 m	2.5 m,
L_*	0.002 m	0.004 m	0.01 m,
L	0.02 m	0.02 m	0.10 m,
L_{mo}	0.04-0.10 m	0.08-0.20 m	0.20-0.50 m
L_{ASL}	0.04-0.12 m	0.08-0.24 m	0.20-0.60 m.

An additional criteria required to avoid secondary circulations imposed by facility size is that the aspect ratio of width to inversion height should be greater than 4. Willis and Deardorff [31] found that at values of 2, results were no longer consistent with an infinitely large homogenous layer.

Based on the previous discussions, the following four similarity criteria appear pertinent to the physical simulation of CBL surface layer circulations:

1. $[Ri_B]_m = [Ri_B]_p$ above the inversion;
2. $[w_*/U]_m = [w_*/U]_p$ in the mixed layer;
3. $[h_s/z_i]_m = [h_s/z_i]_p$;
4. Similar upwind velocity, temperature, and turbulence profiles.

In a CBL situation mechanical and thermal turbulence influence one another in the surface layers. In turn this alters the velocity and temperature profiles throughout the CBL. The bulk Richardson number equality (criterion 1) requires that above the CBL inversion where LSR denotes the prototype-to-model vertical length-scale ratio and subscripts m and p refer to model and prototype conditions, respectively.

$$LSR = \left[\frac{(\partial T/\partial z)_m}{(\partial \theta/\partial z)_p}\right]^{1/2} \left[\frac{\theta_p}{T_m}\right]^{1/2} \left[\frac{U_p}{U_m}\right] \quad (1)$$

The requirement that the convective velocity to advection velocity scale ratio (Criterion 2) is also satisfied implies that

$$LSR = \frac{\beta(z_i)_p \; Q_m}{(w_*)_p^{\;3}} \left[\frac{U_p}{U_m}\right]^3 \tag{2}$$

Similarity of the depth of the CBL (Criterion 3) requires that

$$LSR = \frac{z_{i_p}}{z_{i_m}} \tag{3}$$

Combining the similarity constraints given by the equations for LSR above with the characteristic sizes and flow capacities of the wind tunnels described in Section 3-c and typical atmospheric CBL conditions (See Table 3) provides the relationships and data needed to construct the wind-tunnel operating range and to identify reasonable simulation scenarios. Figures 2 through 10 display performance envelopes for the wind tunnel sizes that are required for CBL surface layer stratification, respectively. The shaded areas are excluded per criteria limitations for CBL simulations. Model plumes produced under CBL conditions in the cross-hatched region may not be turbulent.

Although the smaller MWT can marginally reproduce CBL conditions (Poreh and Cermak [24]: $z_i/L_{mo} \approx 5.6\text{-}10.7$), simultaneous simulation of the surface layer circulations will be unlikely if not impossible. Even for the EWT joint simulation of the CBL and the surface layer regions can only be performed over a limited LSR and U_m range.

It is concluded that an extensive range of wind-tunnel modeling of the three surface layers in a highly unstable atmospheric boundary layer could be achieved with a wind-tunnel working section 5 m high by 10 m wide by 40 m long with 1 MW of floor heating. Model length scale ratios would center about 1/200, with the smallest being about 1/400 and the largest 1/100. The limitations at the small scale are Reynolds number and the practicability of controlling very low wind-tunnel speeds. The limitations at the large scale are mainly the enormous heat requirements and size of the facility needed to model adequate downstream distances from the source.

4. Conclusions

This paper has examined the characteristics, capabilities, and limitations of meteorological wind tunnels to simulate the atmospheric convective boundary layer. A significant conclusion is that such facilities provide an opportunity to explore CBL sublayer and entrainment layer behavior.

Extensive experience with stratified water tanks and wind tunnels definitely suggests that the important turbulence characteristics of the convective boundary layer can be simulated in the laboratory. Nonetheless, laboratory simulation is often not automatic or convenient. Examination of the characteristics of mixing layer entrainment and surface layer behavior determines that:

1. Useful CBL simulations may be obtained in sufficiently large stratified wind-tunnel facilities without augmentation techniques.
2. The use of sufficiently large stratified wind-tunnel facilities will provide a means to study the atmospheric sublayers associated with the CBL.

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Table 3: Prototype Conditions for Convective Boundary Layers (Summarized from various sources)

Pasquill-Gifford Stratification Category		A	B	C
G (m/s)	Geostrophic wind speed	10	10	10
f_c (s^{-1})	Coriolis constant	0.0001	0.0001	0.0001
Z_{ref} (m)	Reference height	10	10	10
Z_t (m)	Troposphere height	10000	10000	10000
T_{air} (°K)	Air temperature	300	300	300
L_{mo} (m)	Monin-Obukhov Length	-5	-10	-20
Ri_f	Flux Richardson No.	-5	-2	-1
Ri	Gradient Richardson No.	-2	-1	-0.5
Fr	Froude No.	-	-	-
μ	Ekman No.	-4000	-120	-60
Z_o (m)	Roughness length	0.01	0.01	0.01
Z_o/L_{mo}		-0.002	-0.001	-0.0005
h (m)	Inversion height	1000	800	600
h/L_{mo}		-200	-80	-30
u* (m/s)	Friction velocity	0.30	0.30	0.30
w* (m/s)	Convective velocity	2.33	2.01	1.65
Φ_m (Z_{ref}/L_{mo})	Dimensionless shear	0.42	0.50	0.59
u* /U		0.073	0.069	0.065
w* /U		0.58	0.40	0.28
U (m/s)	Wind speed, ref height	4	5	6
$d\Theta/dz$ (°C/km)		-10.0	-7.8	-5.6
L_p (m)	Integral length scale	313	313	313
σ_u/w*	X-speed variance	0.4	0.4	0.4
σ_w/w*	Z-speed variance	0.4	0.4	0.4
σ_Θ/T*	Temperature variance	0.2	0.2	0.2
σ_u/u*	X-speed variance	4	3.3	3
σ_w/u*	Z-speed variance	2.39	1.98	1.70
σ_w/σ_u		0.60	0.60	0.57
σ_T/Θ*	Temperature variance	0.75	3.54	4.08
α (Z_o = 0.01)	Power law coef	0.05	0.08	0.1
$Lu_x(Z_{ref})$ (Z_o = 0.01)	X-Integral scale			
λ_w /h	Peak wave length @ ref	0.2	0.2	0.2
ϵ h/w*³	Normalized dissipation	1	1	1

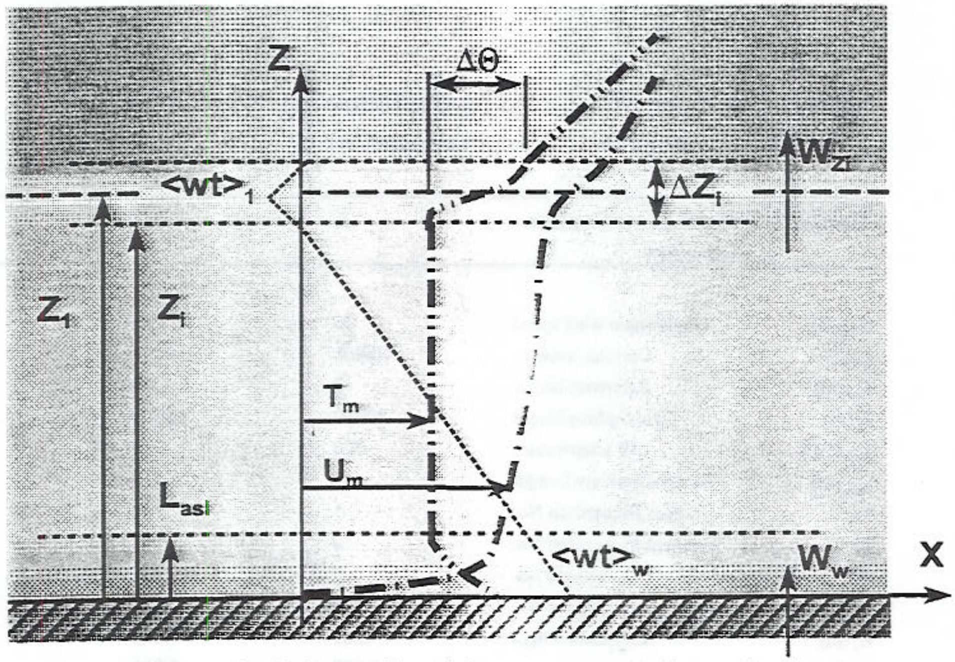

Figure 1: Schematic of the structure of a typical convective boundary layer (CBL)

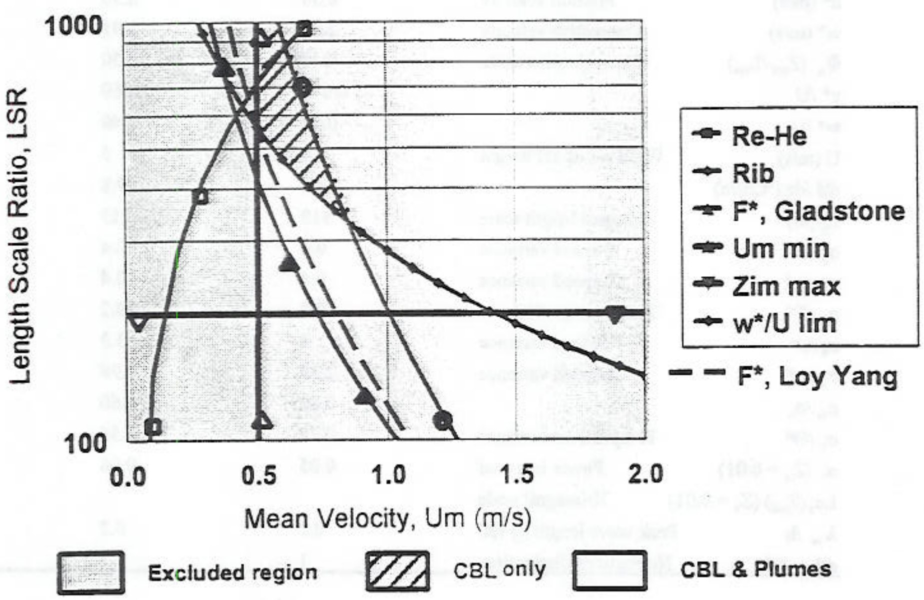

Figure 2: Operating range for CBL simulation of Pasquill Category A conditions in Monash EWT

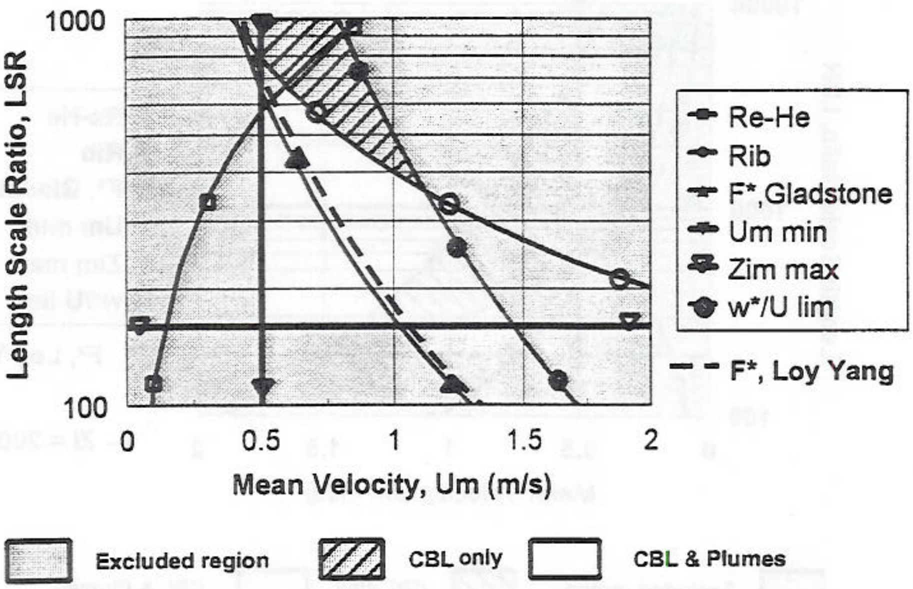

Figure 3: Operating range for CBL simulation of Pasquill Category B in Monash EWT

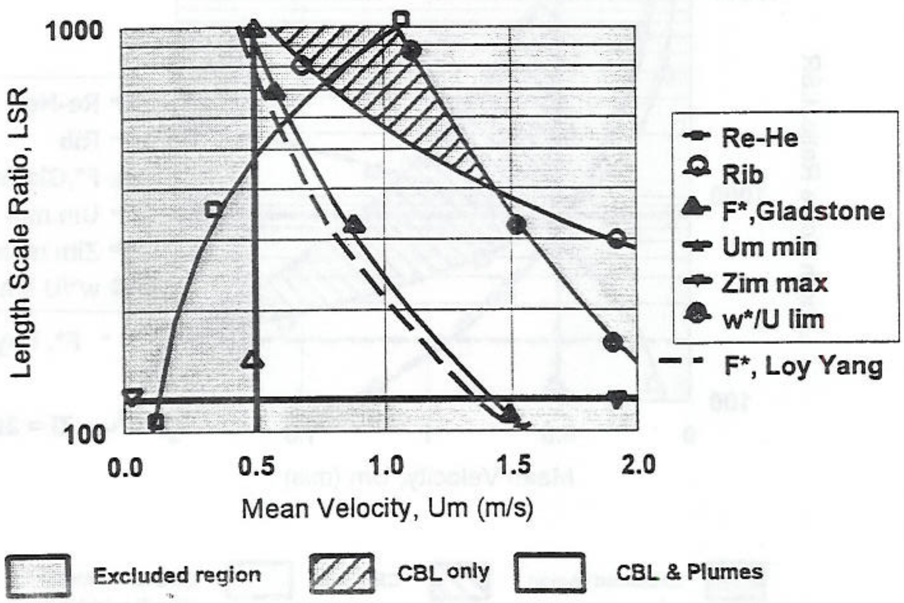

Figure 4: Operating range for CBL simulation of Pasquill Category C in Monash EWT

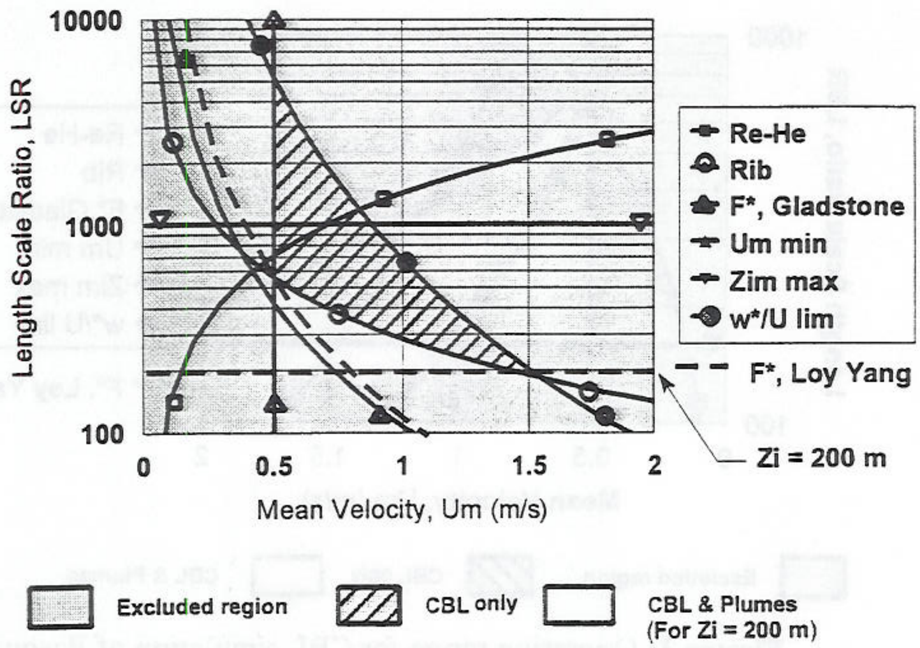

Figure 5: Operating range for CBL simulation of Pasquill Category A in Colorado State MWT

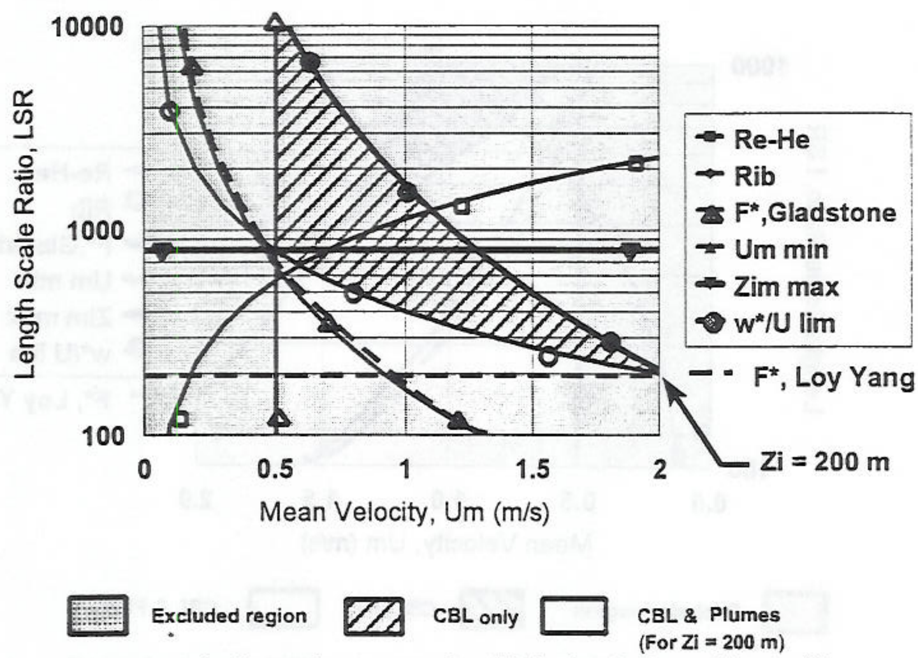

Figure 6: Operating range for CBL simulation of Pasquill Category B in Colorado State University MWT

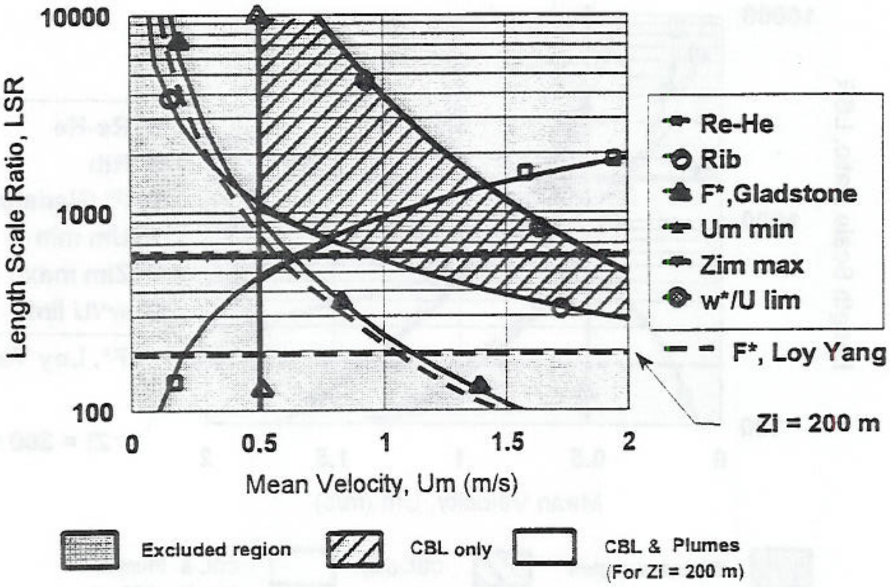

Figure 7: Operating range for CBL simulation of Pasquill Category C in Colorado State University MWT

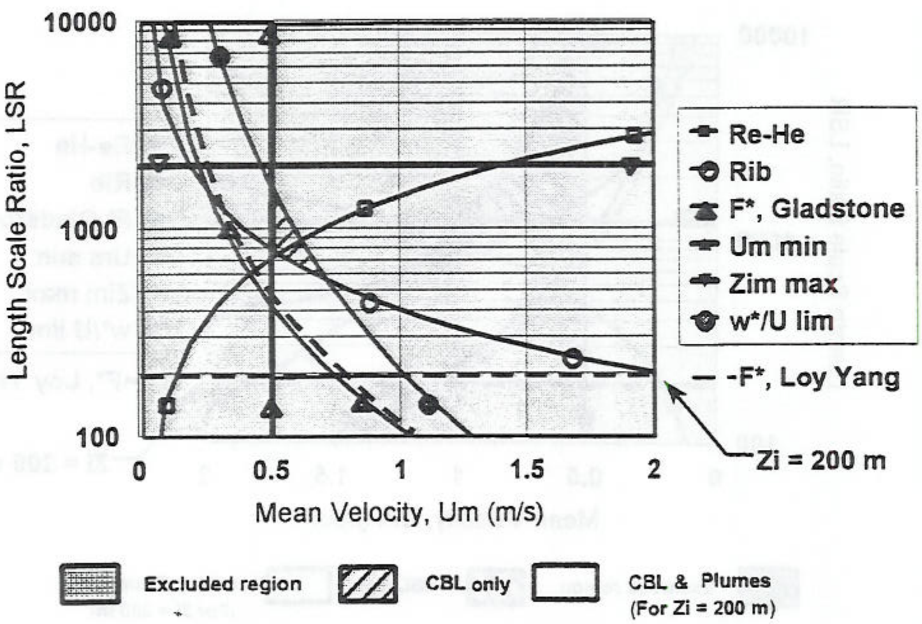

Figure 8: Operating rage for CBL simulation of Pasquill Category A in Karlsruhe SBLWT.

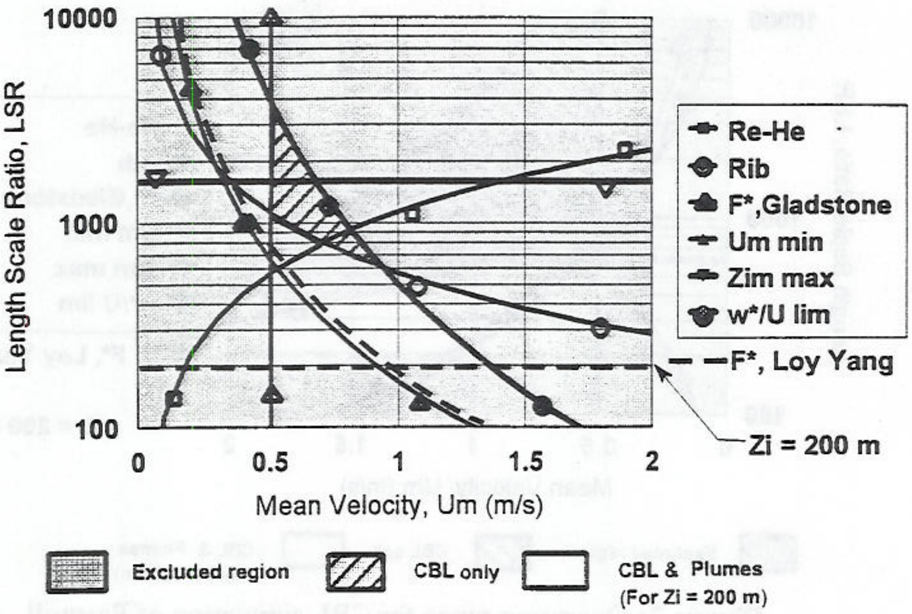

Figure 9: Operating range for CBL simulation of Pasquill Category B in Karlsruhe SBLWT.

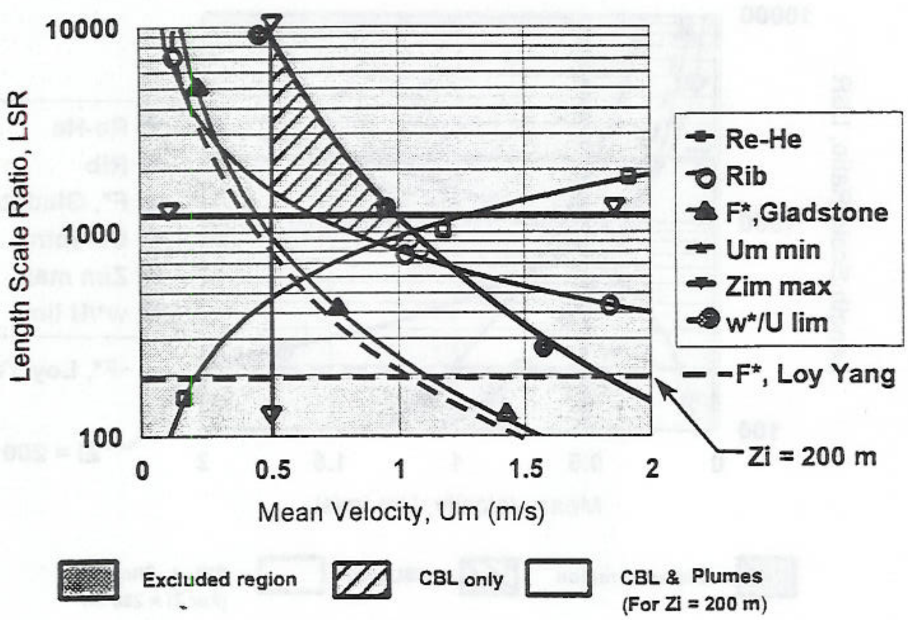

Figure 10: Operating range for CBL simulation of Pasquill Category C in Karlsruhe SBLWT.