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A wind tunnel study of gaseous tracer dispersion in the convective boundary layer capped by a temperature inversion

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Abstract

Results are presented from wind tunnel simulations of gaseous pollutant dispersion in the atmospheric convective boundary layer (CBL) capped by a temperature inversion. The experiments were performed in the thermally stratified wind tunnel of the University of Karlsruhe, Germany. In the tunnel, the case of horizontally evolving, sheared CBL is reproduced. This distinguishes the employed experimental setup from the preceding laboratory and numerical CBL dispersion studies. The diffusive and mixing properties of turbulence in the studied CBL case have been found to be essentially dependent on the stage of the CBL evolution. Effects of the point source elevation on the horizontal variability of the concentration field, and on the ground level concentration as function of distance from the source have been investigated. The applicability of bottom-up/top-down diffusion concept in the simulated CBL case has been evaluated. The influence of surface wind shear and capping inversion strength on the pollutant dispersion and turbulent exchange across the CBL top has been demonstrated. The imposed positive shear across the inversion has been identified as inhibitor of the CBL growth. Comparisons of concentration patterns from the wind tunnel with water tank data are presented. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Plume dispersion; Turbulence; Wind shear; Buoyant forcing; Concentration

1. Introduction

A convective boundary layer (CBL) heated from below and capped by a temperature (density) inversion is a common case of the atmospheric boundary layer during fair-weather daytime conditions. The main mechanism of turbulence production in the CBL is the convective heat transfer from a warm underlying surface. Wind shears at the surface and across the inversion (interfacial) layer are additional contributors to the turbulence generation in the CBL.

The CBL turbulence pattern typically varies both in time and space. However, most of available field measurement, numerical, and laboratory data on the CBL turbulence properties refer to the case of nonstationary (or nonsteady), horizontally homogeneous CBL. For a long time, properties of turbulence in the horizontally evolving CBL have been much less investigated compared to the case of nonsteady CBL.

Characteristics of turbulent flow in the quasi-stationary, horizontally evolving CBL have been extensively studied during the last several years in the thermally stratified wind tunnel of the University of Karlsruhe (UniKa), Germany, by Rau and Plate (1995), Fedorovich et al. (1996), Kaiser and Fedorovich (1998), and Fedorovich and Kaiser (1998). Compared to traditional laboratory water tank approach towards modeling the atmospheric boundary layer convection, wind tunnel models of CBL provide an opportunity to study the combined effects of buoyant and shear forcing on the

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CBL turbulence structure. Wind tunnel experiments at UniKa have shown that wind shears can essentially modify the turbulence dynamics in the CBL and parameters of turbulent exchange across the capping inversion. The buoyancy has been identified in these experiments as dominant mechanism of turbulence production on larger scales of motion, while the role of shear has been increasing towards the range of smaller scales.

The pioneering laboratory experiments on gaseous plume dispersion in the shear-free atmospheric CBL have been performed in the 1970s and 1980s by Willis and Deardorff (1976, 1978, 1981, 1983, 1987), and Deardorff and Willis (1982, 1984) in a convection water tank heated from the bottom. Those studies demonstrated the complexity of dispersion patterns that can be observed in the CBL and their sensitivity to the parameters of the CBL turbulence regime. In order to imitate a mean wind in the CBL, a model stack in the quoted laboratory experiments was towed along the bottom of convection water tank. As a tool for dimensionless analysis and interpretation of plume dispersion pattern in the laboratory CBL, Willis and Deardorff applied the Deardorff (1970) mixed-layer scaling, (further discussed in Deardorff, 1985), which since that time has served as standard framework for intercomparison of CBL dispersion data from different sources.

Recently, Weil et al. (1998) employed a replica of the Deardorff and Willis convection tank for more detailed investigation of plume dispersion in the CBL by using advanced measurement and visualization technique. The new water tank data displayed good agreement with field observations of longitudinal variation of surface concentration and its rms value in the CBL. Parameters of the lateral dispersion of pollutant in the Weil et al. (1998) experiments also conformed well with the field data.

Another type of laboratory facility for convection studies, a saline water tank, has been employed by Hibberd and Sawford (1994a, b), Hibberd and Luhar (1996) for investigation of various CBL dispersion regimes, in particular the plume fumigation into a growing shear-free CBL.

A series of laboratory studies of the plume dispersion in the sheared CBL have been conducted in thermally stratified wind tunnels, see review by Meroney (1998). First wind tunnel experiments of this kind have been carried out in the Colorado State University by Poreh and Cermak (1984, 1985). They have measured parameters of the three-dimensional plume spread in the horizontally evolving CBL and found them to be in fair qualitative agreement with atmospheric observations.

A number of wind tunnel facilities capable of simulating atmospheric CBL have been constructed during the two past decades in Japan. Descriptions of these facilities are given in Ogawa et al. (1981), Sada (1996), and Ohya et al. (1996, 1998). Sada (1996) studied a tracer diffusion in a CBL with weak wind shear using the thermally stratified wind tunnel of Komae Research Laboratory. He found the Deardorff (1970) convective scaling to be applicable to the flow and diffusion patterns in the simulated CBL. The capping temperature inversion in the conducted wind tunnel experiments was rather weak. That was a reason for substantial vertical spread of the plume in the upper portion of the wind tunnel CBL.

However, in the aforementioned wind tunnel studies, the experimentally obtained parameters of dispersion were not analyzed in conjunction with properties of turbulence in the simulated CBL, and effects of flow shear on the tracer diffusion in the CBL were not particularly investigated.

The objectives of the present study are: (i) to evaluate the applicability of the UniKa wind tunnel for modeling plume dispersion in the atmospheric CBL, and (ii) to experimentally identify contributions of surface and elevated wind shear to the diffusion regime in the inversion-capped CBL. Results of the wind tunnel experiments will be analyzed in comparison with data from other laboratory and numerical studies of turbulent flow and diffusion in the atmospheric CBL.

2. Experimental setup

The UniKa thermally stratified wind tunnel is a facility of the close-circuit type, with 10-m long, 1.5-m wide and 1.5-m high test section. The return section of the tunnel is subdivided into ten layers, which are individually insulated. Each layer is 15-cm deep and is driven by its own fan and heating system. In this manner, the velocity and temperature profiles can be preshaped at the inlet of the test section as shown in Fig. 1. A feedback control system compensates disturbances in the flow while it passes through the return section and enforces quasi-stationary inlet conditions for the flow entering the test section. The test section floor, which is constructed of aluminum plates, can be heated with a preset energy input to produce a constant heat flux through the CBL bottom.

In the basic wind tunnel experimental configuration (Fedorovich et al., 1996), the two lower layers of the tunnel, of 0.3 m depth in total, operate in the open-circuit regime with the incoming flow possessing the temperature of the ambient air (about 300 K). Between the second and the third layers a temperature jump of 30 K is imposed. The temperature of each of the subsequent layers is regulated in order to produce a temperature gradient of $33\,\mathrm{K\,m^{-1}}$ (5 K/layer) in the upper flow region. The incoming flow velocity in all layers is set equal to $1\,\mathrm{m\,s^{-1}}$. The kinematic heat flux

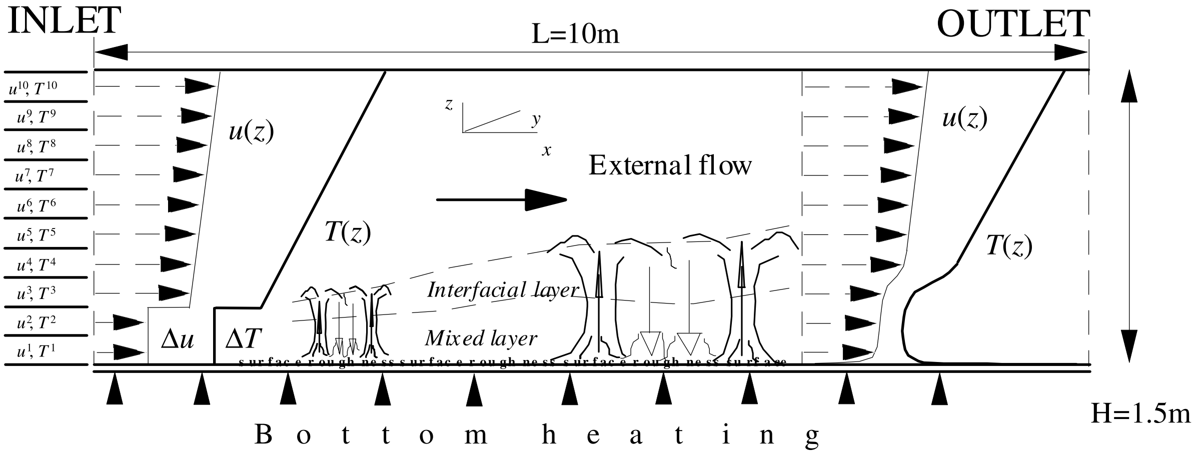

Fig. 1. Sketch of modeling the horizontally evolving atmospheric CBL in the UniKa thermally stratified wind tunnel.

through the bottom is kept constant, at the level of approximately $1\,\mathrm{K\,m\,s^{-1}}$.

The CBL in the tunnel develops through several intermediate regimes that are described in Fedorovich et al. (2001a). The main of these regimes are: (a) stage of unstable surface layer extending up to $x \approx 3.5\,\mathrm{m}$ downwind from the inlet; (b) transition zone within a distance range from roughly 3.5–5.5 m, where a fast mixing of the flow beneath the inversion occurs; and (c) stage of quasi-homogeneous, slowly evolving CBL downwind of $x \approx 5.5$. The last stage is the closest counterpart of the atmospheric CBL as shown in Fedorovich et al. (1996).

In order to illustrate the main features of turbulence regime in this portion of the wind tunnel CBL we show in Fig. 2 a selection of turbulence statistics from the tunnel compared with corresponding statistics from several other experimental and numerical CBL studies. Some additional turbulence statistics from the wind tunnel CBL model may be found in Fedorovich et al. (1996). The plotted statistics are normalized by the Deardorff (1970) convective scales, which are z_i for length, $w_* = (\beta Q_s z_i)^{1/3}$ for velocity, and $T_* = Q_s/w_*$ for temperature. In the above expressions, z_i is the CBL depth scale traditionally defined as elevation of the heat flux minimum within the inversion layer, $\beta = g/T_0$ is the buoyancy parameter (g is the gravity acceleration, T_0 is the reference temperature), and Q_s is the near-surface value of the turbulent kinematic heat flux.

In the plot with horizontal velocity variances (Fig. 2a), the comparatively large $\overline{u'^2}$ values at small z in the wind tunnel CBL are apparently caused by additional turbulence production in the lower CBL portion due to surface shear. The contribution of surface shear to the turbulence production may be expressed in terms of shear/buoyancy production ratio u_*/w_*, where u_* is the surface friction velocity. In the UniKa wind tunnel CBL model this ratio is in the range from 0.2 to 0.5. This corresponds to the range of $|L|/z_i$ values from 0.02 to 0.3, where $L = -u_*^3/(k\beta Q_s)$ is the Monin–Obukhov length scale and k is the von Kármán constant, see Fedorovich et al. (1996). In a pure shear-free CBL ($u_*/w_* = 0$) that was numerically simulated by Schmidt and Schumann (1989), the horizontal velocity variances close to the surface are obviously smaller. Demonstrated velocity fluctuations from the water tank and atmospheric CBLs are rather large in the middle portion of the layer. As mentioned in Kaiser and Fedorovich (1998), horizontal velocity fields in these cases have been presumably contaminated by imposed instabilities of different kinds.

In the upper portion of the CBL, at z/z_i close to 1, a sideward transport of air from the rising thermals squashed by inversion is the chief reason for the enhancement of horizontal velocity fluctuations. In the CBL studies, the capping effect of inversion on the CBL evolution is commonly expressed through the dimensionless Richardson number $Ri_{\Delta T} = \beta w_*^{-2} z_i \Delta T$ based on the temperature increment ΔT across the inversion. It is easy to show that $Ri_{\Delta T}$ is actually a scaled equivalent of ΔT. The wind tunnel data and accompanying numerical results for the CBL with moderate capping inversion ($Ri_{\Delta T} \approx 10$) predict merely a bend in the $\overline{u'^2}$ profile at the inversion level. In the $\overline{u'^2}$ profiles from numerical and water tank shear-free CBLs with stronger capping inversions ($Ri_{\Delta T}$ of the order of 100) the enhancement of horizontal velocity fluctuations at the CBL top is much more pronounced.

Regime of vertical velocity fluctuations in the CBL is dominantly governed by buoyant forcing. This is the reason why the CBL vertical velocity variance (Fig. 2b) is less affected by wind shears as compared to $\overline{u'^2}$, and

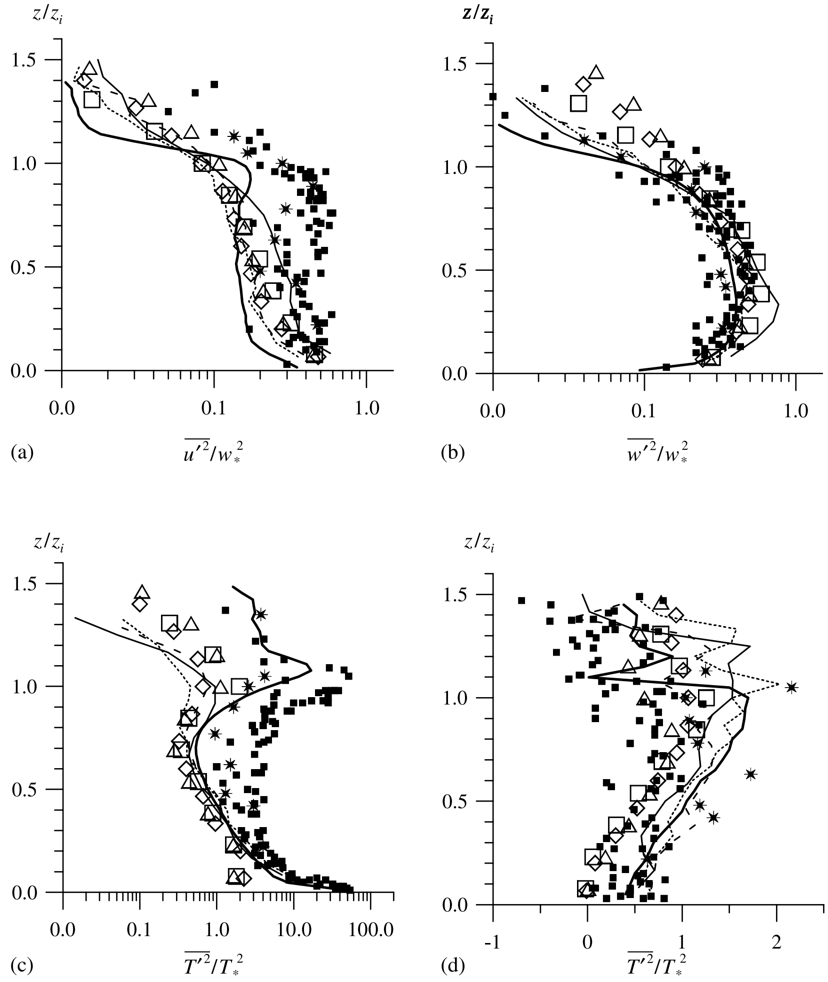

Fig. 2. Longitudinal (a), vertical (b) velocity, temperature (c) variances, and vertical velocity skewness (d) in the quasi-homogeneous portion of the wind tunnel CBL ($x = 3.98$ m—solid lines; $x = 5.63$ m—dashed lines, and $x = 7.28$ m—dotted lines) compared with data from other related CBL studies. Numerical data of Fedorovich et al. (2001a) referring to the same locations in the tunnel are given by open squares, triangles, and diamonds, respectively. Shear-free CBL data from LES of Schmidt and Schumann (1989, heavy solid lines) and water tank model of Deardorff and Willis (1985, asterisks) are shown together with atmospheric data (filled squares) from Lenschow et al. (1980) in (a) and (b), Caughey and Palmer (1979) in (a)–(c), and Sorbjan (1991) in (d).

the scatter of $\overline{w'^2}$ values originating from different CBL studies is rather small. One may notice, however, that at $x = 3.98$ m, which is in the lee region of transition zone, the wind tunnel and LES variances are somewhat exaggerated compared to their values in other locations.

The post-transition effects can be found also in the measured and computed temperature variance profiles (Fig. 2c). The magnitude of $\overline{T'^2}$ maximum at the inversion level is markedly larger just behind the transition region, where the inversion is stronger and entrainment is more active than in the quasi-homogeneous CBL downwind. The influence of inversion strength on the magnitude of temperature fluctuations at the CBL top is clearly illustrated by comparison of temperature variances originating from different data sources. Atmospheric, water tank, and LES data from CBLs with relatively large $Ri_{\Delta T}$ provide roughly ten times higher values of $\overline{T'^2}$ at the CBL top than the ones observed in the wind tunnel CBL and its LES counterpart.

Vertical velocity field in the CBL is known to be persistently skewed (Lenschow, 1998): it is composed of narrow, fast rising thermals and broad, slow downdrafts. This characteristic asymmetry of w field in the atmospheric CBL and in the variety of its model analogs is demonstrated in Fig. 2d. Vertical distribution of skewness values from the atmospheric measurements clearly points to a more homogeneous vertical structure of up- and downdrafts in the atmospheric CBL compared to convection cases reproduced numerically and in the laboratory. The skewed distribution of w fluctuations makes inapplicable in the CBL case the traditional Gaussian approximations of w probability density functions employed in models of atmospheric dispersion under neutral conditions (Lamb, 1982; Vinther Jensen and Gryning, 1998).

From the shown examples of turbulence statistics from the wind tunnel one may conclude that dynamic and thermal structure of turbulence in the main portion of the simulated CBL is in fair agreement with its atmospheric observations. The wind tunnel data also reasonably correspond to the data from other numerical and laboratory studies of the CBL turbulence structure. Besides that, the wind tunnel turbulence statistics reflect specific features of the turbulence regime in the CBL with wind shear.

Special measurements performed over the (y–z) planes of the tunnel have shown that except for the relatively thin (of the order 0.2 m) near-wall regions the turbulence regime in the simulated CBL is rather uniform across the flow. The characteristic magnitudes of mean w and v in the test section are about $0.04\,\mathrm{m\,s^{-1}}$ that is much smaller than the typical rms value of the w fluctuations ($0.15\,\mathrm{m\,s^{-1}}$). The cross-stream averages of w and v are close to zero.

For the diffusion experiments in the tunnel, a nonbuoyant tracer has been used. As tracer gas, SF_6 has been employed. The mixture of tracer gas with air has been emitted from a pipe outlet mounted at different elevations inside the simulated CBL and above it. In the experiments discussed below the source was placed in the central vertical plane of the tunnel, at 3.32-m distance from the test section inlet, close to the downwind edge of the CBL transition zone. Concentration measurements have been carried out by standard technique using electron detector method. The measured concentration values have been averaged over 2-min long time periods.

3. Plume dispersion in the wind tunnel CBL

3.1. *Influence of plume elevation on the concentration distribution*

Willis and Deardorff (1978) found in their water tank experiments that the source location is an important factor of the concentration distribution in the CBL. They have shown, see also Lamb (1982), that the average centerline of the plume released from an elevated source in the CBL descends quickly downwind of the source. In contrast, the plume released near the surface rises fast inside the CBL. These observations, which are not consistent with predictions of the Gaussian plume model, manifest the aforementioned specific character of dispersion in the CBL associated with the skewed vertical velocity field.

The discussed feature of plume dispersion in the CBL is illustrated in Fig. 3, where concentration patterns obtained in the wind tunnel CBL are plotted together with their counterparts form the water tank model of Willis and Deardorff (1978). All presented patterns are normalized with the Deardorff (1970, 1985) convective scales. From the qualitative point of view, the concentration distributions provided by both experimental techniques fairly agree with each other. However, a closer inspection of plots reveals the smaller horizontal concentration gradients in the lower portion of wind tunnel CBL affected by surface shear. This is apparently a result of enhanced lateral transport of tracer by comparatively large horizontal velocity fluctuations associated with shear.

It should be noted here that horizontal velocity fluctuations in the dispersion study of Willis and Deardorff (1978) presumably conducted with the CBL experimental setup of Willis and Deardorff (1974) have been markedly smaller than in the experiments of Deardorff and Willis (1985). This was primarily caused by too small (of the order of 2) ratio between the laboratory tank width and the CBL depth in the experiments of the 1970s. In the later study of Deardorff and Willis (1985), where the $\overline{u'^2}$ values shown in Section 2 (Fig. 2) were obtained, this ration was much larger, of the order of 5.

At the same time, the capping inversion strength in water tank experiments of Willis and Deardorff (1978) was in terms of $Ri_{\Delta T}$ an order of magnitude larger that in the UniKa wind tunnel. The effect of capping inversion on the vertical diffusion of tracer is clearly seen in the upper portions of concentration distributions shown in Fig. 3. The decay of concentration with height in the wind tunnel is not as abrupt as in the water tank, where a comparatively strong inversion effectively blocks the vertical transport. The enhancement of horizontal velocity fluctuations in the upper portion of water tank CBL with stronger capping inversion (see discussion in the previous section) is an apparent reason for more homogeneous longitudinal concentration distribution at the level of inversion than in the wind tunnel CBL with weaker capping inversion.

The effect of source elevation on the plume dispersion in the horizontally evolving CBL is further illustrated in Fig. 4. Two upper plots show concentration distributions from two sources contrastingly placed at the CBL bottom and at the level of capping inversion. The concentration values in the plots are normalized by $E_s/(L^2U)$, where E_s is the source strength in $\mathrm{m^3\,s^{-1}}$, and $L = 1\,\mathrm{m}$, $U = 1\,\mathrm{m\,s^{-1}}$ are,

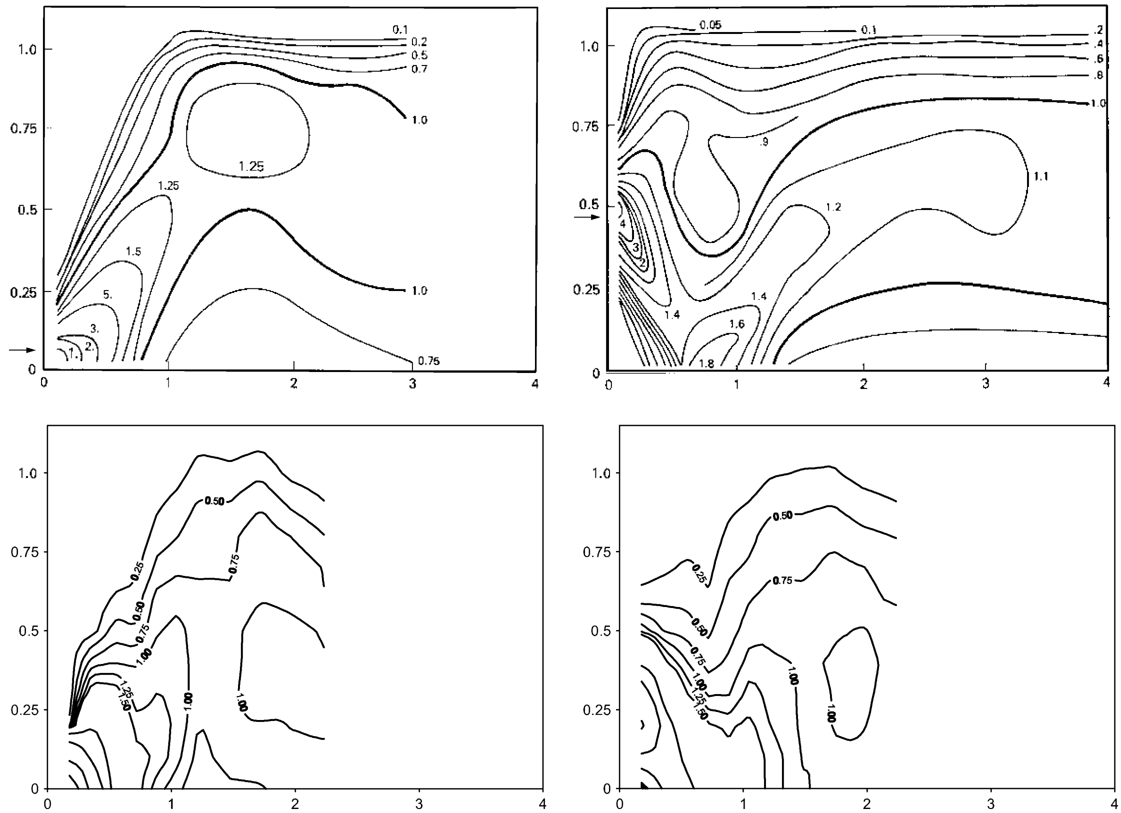

Fig. 3. Dispersion of nonbuoyant plume in the water tank model of shear-free CBL (Willis and Deardorff, 1978, upper plots) and in the UniKa wind tunnel CBL (lower plots). Source elevations are $z/z_i = 0.07$ (left-hand plots) and $z/z_i = 0.5$ (right-hand plots). Heights are normalized by z_i, lengths by $(z_i U)/w_*$, and concentration values by $Q_s/(z_i^2 U)$. The origin of the x ordinate is at the source location.

respectively, characteristic length and velocity scales of the wind tunnel flow.

Wyngaard and Brost (1984) were first to demonstrate that properties of turbulent transport of the passive scalar emitted near the CBL bottom (bottom-up diffusion) are rather different to the transport of scalar emitted at the inversion level (top-down diffusion). In the shown concentration patterns from the wind tunnel CBL one may clearly see slow top-down diffusion of tracer from the elevated source and relatively active bottom-up transport of tracer material that was released near the surface. In the first case, the line of maximum concentration roughly follows the inversion level, whilst in the case of surface release the maximum concentration values downwind of the source are observed in the middle portion of the CBL. From the top, the tracer diffusion in both cases is blocked by the capping inversion. In the literature, see for instance Sorbjan (1989), the diffusion regime observed in the case of elevated source is commonly referred to as fumigation.

When the source is moved further upwards and the tracer is emitted well above the capping inversion (the lowest plot of Fig. 4.), only negligible amount of tracer material is entrained downwards into the capping inversion of growing CBL. In this case, the plume dispersion is maintained by weak turbulent motions suppressed by stable stratification inside the inversion layer and in the outer flow above it. Such diffusion regime is usually called fanning (Sorbjan, 1989).

3.2. Ground level concentration distribution

In Fig. 5, we show ground level concentration pattern in the CBL together with the dispersion pattern from the source of the same elevation placed in the neutrally stratified boundary layer (NBL). The neutral layer has been simulated in the UniKa wind tunnel for comparison purposes. The mean flow velocity and the surface roughness in the case of neutral boundary layer are the same as in the CBL case. Both concentration distributions presented in Fig. 5 are normalized by $E_s/(L^2 U)$.

It is easy to see that high concentration levels at the surface in the CBL are found at much smaller distances from the source than in the neutral layer case. The principal reason for that is the aforementioned asymmetry of the probability density distributions of the

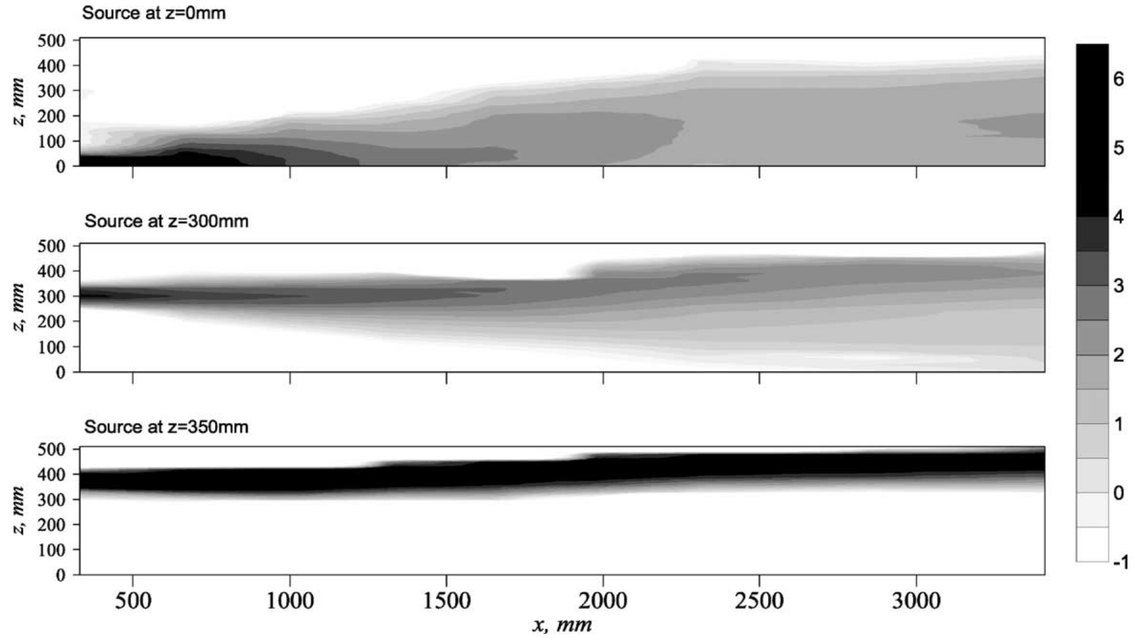

Fig. 4. Influence of the source elevation on the longitudinal distribution of concentration in the wind tunnel CBL. The origin of the x ordinate is at the source location. The capping inversion height at $x = 0$ is 300 mm for all cases shown.

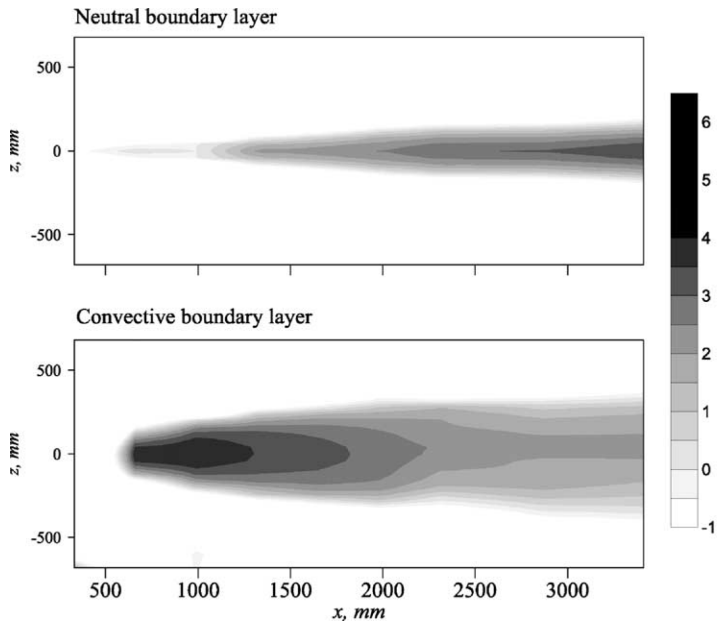

Fig. 5. Surface concentration distributions in the neutrally stratified and convective boundary layers. The source elevation ($z = 100$ mm) is the same in both cases. The origin of the x ordinate is at the source location. The CBL experimental setup corresponds to the basic flow configuration (see Section 2 and Fedorovich et al., 1996).

vertical velocity in the CBL. Descending motions (downdrafts), no matter how weak they are compared with narrower and faster updrafts (thermals), are statistically dominant in the CBL. Due to this, the major portion of tracer material released from a source in the bulk of CBL first descends over some distance and thus produces high concentration levels close to the surface. Eventually, however, the descending tracer particles enter updrafts that transport them upwards. With more tracer material carried away from the surface by thermals, the line of maximum concentration rises towards the middle of the layer and the ground level concentration decreases.

In this respect, the horizontal evolution of the ground concentration field in the lower plot of Fig. 5 is consistent with our earlier observations of the dispersion from elevated source in Figs. 3b and d. Contrary to the CBL, the ground level concentration within the NBL gradually increases along the centerline of the plume throughout the whole range of distances shown in the plot.

The footprint of the plume in the neutral layer is considerably narrower than its CBL counterpart. Apparently, this is a result of enhancement of the lateral component of turbulent motion in the CBL due to the buoyant forcing. The cross-flow concentration distribution at the surface in the NBL retains approximately the Gaussian shape, whilst the CBL concentration distribution is somewhat flat in its central part and squeezed from both sides. Such channeling of the plume in the CBL case is probably caused by longitudinal semi-organized roll-like motions that are common for the atmospheric CBL with wind shear. Analogous motions have been observed in the UniKa wind tunnel model of the CBL (Fedorovich et al., 1996). Their effects on the CBL flow regime have been comprehensively analyzed by Kaiser (1996).

3.3. Plume dispersion in the presence of elevated wind shear

Wind shear across the capping inversion (we also call it the elevated wind shear) is an additional mechanism of the turbulence regime modification in the CBL. Elevated shears are common for atmospheric CBL under baroclinic conditions (Stull, 1988).

Wind tunnel experiments of Fedorovich and Kaiser (1998) have demonstrated that turbulence enhancement in the upper portion of CBL with elevated shear may be accompanied by the alteration of vertical turbulent transport across the capping inversion. Such effect of elevated shear can be associated with the so-called shear sheltering of turbulence (Hunt, 1998). Due to technical limitations of the UniKa wind tunnel, experiments of Fedorovich and Kaiser (1998) have been restricted only to the case of positive elevated shear, when the mean flow above the inversion possesses higher momentum than mean motion in the CBL. On the other hand, numerical simulations of Fedorovich et al. (2001b) have provided an indication that the CBL growth dynamics and properties of turbulent exchange across the sheared inversion can essentially depend on the sign of elevated shear. With negative elevated shear, the CBL growth has been found to be more active than in the case of CBL with shear-free capping inversion.

Our recent re-inspection of numerical simulation results from Fedorovich et al. (2001b) has shown that the main mechanism responsible for alteration of the CBL growth in the presence of elevated wind shears is the entrainment of momentum across the sheared inversion. Such entrainment locally accelerates or decelerates flow in the main portion of the CBL depending on the sign of shear. Resulting convergence or divergence of flow below the inversion leads to organized ascending or descending motions at the level of inversion. In the first case, with negative elevated shear, these motions contribute to the vertical expansion of the CBL. In the second case, with positive elevated shear, they push the inversion down and thus hamper the entrainment process.

In order to study the effect of positive elevated shear on the plume dispersion across the upper interface of the wind tunnel CBL, a positive mean velocity increment of $0.5\,\mathrm{m\,s^{-1}}$ has been generated in the incoming flow at the level of initial temperature inversion, that is between the second and the third layers of the tunnel. The details of this experimental setup are given in Fedorovich and Kaiser (1998). Location of the source in the case of sheared inversion has been the same as in the previously described experiments with zero shear across the inversion.

In Fig. 6, a dispersion pattern obtained in the case of elevated shear (lower plot) is compared with its analog for the case of CBL with shear-free upper interface (upper plot). This comparison clearly demonstrates that elevated positive shear additionally hampers the plume penetration above the inversion in the horizontally evolving CBL and leads to a pronounced blocking of the tracer within the CBL. The resulting concentration levels at same elevations along the wind tunnel test section are noticeably smaller in the case of sheared inversion than in the CBL capped by shear-free density interface. As one may also notice, the rise of maximum concentration line in the case of sheared inversion is delayed in comparison with the reference shear-free case. The enhanced horizontal velocity fluctuations inside the sheared inversion (Fedorovich and Kaiser, 1998) lead to comparatively smooth horizontal distribution of concentration in the upper portion of CBL with elevated shear (lower plot in Fig. 6).

Generally, the observed features of plume dispersion in the CBL with positive elevated shear are in conformity with properties of turbulent flow regime in this CBL type that has been experimentally and numerically studied by Fedorovich et al. (2001b). Based on numerical results from this study it would be logical to suppose that in the case of negative elevated shear the vertical extension of polluted region will be enhanced compared to the situation with shear-free inversion.

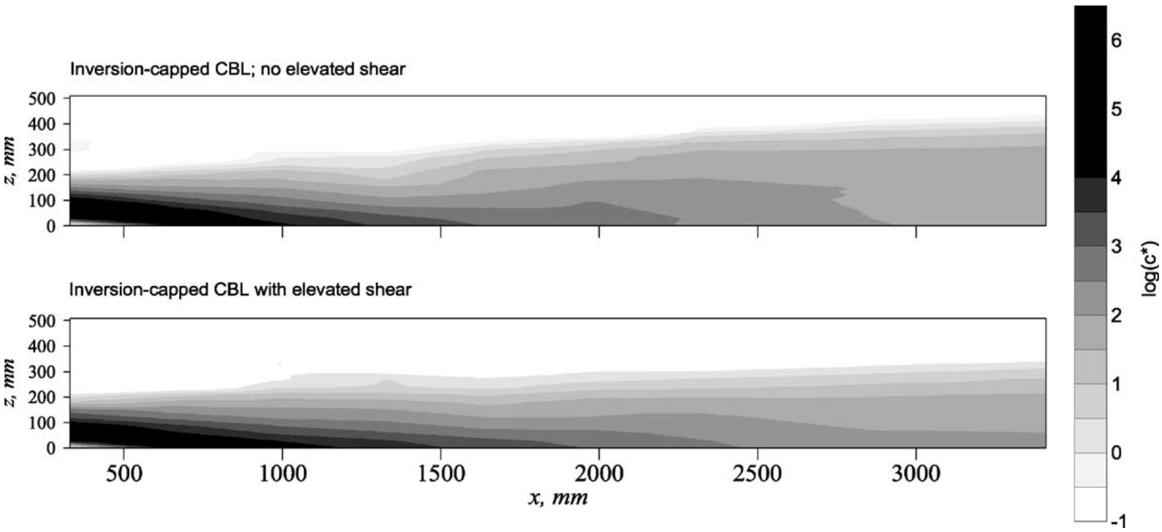

Fig. 6. Longitudinal concentration distributions in the CBL with and without elevated flow shear. The source elevation is 100 mm in both cases. The origin of the x ordinate is at the source location. The capping inversion and shear zone elevations at $x = 0$ are 300 mm.

However, such supposition has to be additionally supported by field and/or laboratory experimental data. Complementary numerical studies of directional effect of shear on the tracer transport across the capping inversion can be also useful.

4. Summary and conclusions

In the reported study, the properties of gaseous plume dispersion in the quasi-stationary, horizontally developing CBL with wind shear have been investigated and analyzed in conjunction with observed characteristics of the CBL turbulence regime. The investigated CBL case has been reproduced in the thermally stratified wind tunnel of the University of Karlsruhe, Germany.

The capping inversion strength and surface wind shear have produced a significant impact on the plume dispersion pattern in the CBL. With relatively weak capping inversion in the wind tunnel CBL characterized by the convective Richardson number of the order of 10 and less, the decay of concentration with height across the inversion has been markedly more gradual than in the water tank CBL with an order of magnitude stronger inversion.

The longitudinal distribution of concentration in the upper portion of wind tunnel CBL was less homogeneous than in the water tank CBL with more active horizontal turbulent transport at the inversion level. On the other hand, the comparatively small horizontal variability of concentration field in the lower portion of wind tunnel CBL has been apparently caused by contribution of surface shear to amplification of horizontal turbulent exchange in the lower portion of CBL.

The Wyngaard and Brost (1984) concept of asymmetry between the bottom-up and top-down diffusion of tracer in the atmospheric CBL has been supported by concentration measurements in the wind tunnel CBL model.

Due to enhancement of the lateral component of turbulent motion associated with the buoyant forcing, the footprint of the plume in the CBL has been found to be considerably broader than its counterpart in the neutral boundary layer with analogous mean transport properties. The cross-stream concentration distribution in the CBL has displayed features of plume channeling that has been presumably caused by longitudinal semi-organized roll-like motions in the sheared CBL.

In the CBL case with the above-inversion flow possessing a higher velocity than the mean motion inside the CBL (the case of positive elevated shear), the CBL growth has been notably weaker compared to the CBL with shear-free inversion. This has resulted in higher near-ground concentration values in the CBL with sheared capping inversion. At the same time, the enhanced horizontal exchange associated with elevated shear has provided more homogeneous longitudinal distribution of concentration in the upper portion of the CBL than in the CBL without elevated wind shear.

Further laboratory and numerical studies are needed to better understand the physical nature of different forcing mechanisms affecting the plume dispersion in the sheared atmospheric CBL. The effect of elevated shear and the influence of associated ascending and descending organized motions on the dispersion across the capping inversion of CBL can be pointed as topics of particular interest for these studies.

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