

Laboratory and Numerical Modeling of Stably Stratified Wind Flow Over Water Surface



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Abstract The objective of this chapter is to perform laboratory and direct numerical modeling of turbulent wind over water surface under stable stratification conditions. Laboratory and numerical experiments are performed under the same bulk Reynolds and Richardson numbers which allow a direct comparison between the measurements and calculations. The laboratory experiments are performed in a wind-wave flume on the basis of a thermostratified tank facility at IAP RAS. A sufficiently strong stable stratification (with the air–water temperature difference of up to 18 K) and a comparatively large bulk Richardson number (up to $Ri \approx 0.04$) in the experiment are created by heating the incoming air flow while maintaining a relatively low wind speed (up to 3 m/s) and the corresponding bulk Reynolds number up to $Re \approx 60000$. The air velocity field is retrieved by employing both contact (Pitot tube) and PIV methods, and the air temperature profile is measured simultaneously by a set of contact probes. The same bulk Ri and Re are prescribed in direct numerical simulation where turbulent Couette flow is considered as a model of the near water constant stress atmospheric boundary layer. The mean velocity and temperature profiles obtained in our laboratory and numerical experiments agree well and also are well predicted by the Monin–Obukhov similarity theory. The results show that sufficiently strong stratification, although allowing a statistically stationary turbulent regime, leads to a drastic reduction of both turbulent momentum and heat fluxes. Under this regime, the flow turbulent Reynolds number (based on the Obukhov length scale and friction velocity) is found to be in agreement with known criteria characterizing stationary strongly stratified turbulence.

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1 Introduction

Detailed knowledge of the properties of small-scale processes occurring in atmospheric boundary layer over water surface is important for correct parameterization of turbulent exchange in marine atmospheric boundary layer in large-scale weather and climate prognostic models. Under the conditions of relatively small (about several degrees of K) air–water temperature difference and sufficiently high wind speed (typically, about several m/s) the air flow in the boundary layer (BL) is weakly stratified and turbulent, and its properties are well predicted by the Monin–Obukhov similarity theory (MOST) [7]. Of special interest are subcritical regimes under a sufficiently strong stratification, where the flow is still statistically stationary and turbulent although turbulent momentum and heat fluxes are drastically reduced as compared to the weakly stratified flow. In practice, such BL regime can be realized, for example, when a relatively warm inland air is advected over a cooler sea or lake in the spring season wherein the air–water temperature difference can become quite significant (more than 10 K) to render stratification effects to become strong at sufficiently low winds (about or below 3 m/s) [1, 2].

Available field observations and laboratory experimental measurements show that strong stable stratification effectively suppresses turbulent momentum and heat fluxes in the boundary layer as compared to the weakly stratified turbulent regime under which MOST parameterization is still applicable [3]. Detailed experimental measurements of the velocity and temperature profiles in the stably stratified boundary layer, both for weakly stratified and strongly stratified regimes, were performed by Ohya et al. [4]. In this experiment, the air flow over a cooled flat solid floor in thermally stratified wind tunnel was investigated. The bulk inflow air velocity U_0 was in the range from 0.8 m/s to 3 m/s and the difference between the air and surface temperatures ΔT was in the range from 46 to 53 K with the resulting bulk Reynolds number $Re = O(10^4 \div 10^5)$ and bulk Richardson number $Ri = O(0.1 \div 1)$. These experimental results suggest that under the influence of stable stratification the air velocity in the boundary layer, normalized by the free-stream air velocity, is decreased as compared to the non-stratified flow. The results also show that turbulent momentum flux was reduced by strong stable stratification as compared to the neutrally stratified flow case. However, there was no comparison given between the experimental results obtained under strong stratification conditions and predictions of MOST.

In our earlier study, we investigated stably stratified turbulent flow over water surface by performing direct numerical simulation (DNS) for a range of bulk Richardson and Reynolds numbers [5]. DNS does not require any parameterization and resolves all physically relevant flow scales up to viscous dissipation (Kolmogorov) length. At sufficiently small Ri , DNS reproduces statistically stationary turbulent regime with vertical profiles of mean velocity and temperature obeying the Monin–Obukhov similarity theory. At large Ri turbulence degenerates. We investigated the transition from turbulent to laminar regime as dependent on both Reynolds and Richardson numbers, and compared our results with those of the previous study by Flores and Riley [6]. These authors compiled available laboratory and numerical data and performed

DNS of their own to analyze the transition from turbulent to laminar regime in terms of a *turbulent Reynolds number*, Re_L , based on the Obukhov length scale and friction velocity. The basic result obtained by Flores and Riley [6] is that the stationary turbulent regime is maintained at $Re_L > 100$; otherwise turbulence degenerates and the flow becomes laminar. Our DNS confirmed this conclusion. However, there is still an insufficient knowledge of a threshold regime, where BL can still be regarded in a statistically stationary turbulent regime, where MOST predictions still correctly predicts the flow properties. This study aims at laboratory and numerical study of such regimes.

We perform both laboratory modeling and DNS of turbulent air wind over water surface under both weak and strong stable stratification conditions. The laboratory and numerical experiments are performed under the same bulk Reynolds and Richardson numbers which allow a direct comparison between the measurements and DNS results. The laboratory experiment is performed in a wind-wave flume on the basis of a thermostratified tank facility at IAP RAS. A sufficiently strong stable stratification (with the air–water temperature difference up to 18 K) and a comparatively large bulk Richardson number (up to $Ri \approx 0.04$) in the experiment is created by heating the incoming air flow while maintaining a relatively low wind speed (up to 3 m/s) and the corresponding bulk Reynolds number up to $Re \approx 60000$. The air velocity field is retrieved by employing both contact (Pitot) and PIV methods, and the air temperature profile is measured simultaneously by a set of contact probes. The same bulk Ri and Re are prescribed in DNS. The mean velocity and temperature profiles obtained in laboratory and numerical experiments, for both regimes of weak and strong stratification, agree well and also are well predicted by the Monin–Obukhov similarity theory. The results also show that under strong stratification conditions, both turbulent momentum and heat fluxes are drastically reduced as compared to the weak stratification regime.

The chapter is organized as follows. In the next Sect. 2, for convenience, we briefly formulate the predictions of Monin–Obukhov similarity theory (MOST) for weakly stratified BL flow. In Sect. 3, laboratory and numerical experimental settings are presented, and the results are discussed. Section 4 contains discussion and conclusions.

2 MOST Predictions for Velocity and Temperature Profiles in Weakly Stratified BL Flow

Stably stratified boundary layers typically are classified as *weakly stable* if buoyancy effects are weak enough to allow a statistically stationary turbulent regime [3]. In this weakly stratified boundary-layer flow, the dependence of the mean velocity $U(z)$ and the deviation of mean temperature from its surface value, on height z in the region of constant turbulent stresses are described by the Monin–Obukhov similarity theory (MOST) (cf. [7]) as

$$\frac{U(z)}{u_*} = \frac{1}{\kappa} \left(\ln \frac{z}{z_{0U}} + C_U \frac{z}{L} \right), \quad (1)$$

$$\frac{T(z) - T_0}{T_*} = \frac{\text{Pr}_t}{\kappa} \left(\ln \frac{z}{z_{0T}} + C_T \frac{z}{L} \right), \quad (2)$$

where κ is the von Karman constant, C_U and C_T are empirical dimensionless constants and Pr_t is the turbulent Prandtl number. The common estimates are $\kappa = 0.4$, $C_U = 2$, $C_T \sim C_U$, and $\text{Pr}_t = 0.85$ as observed in most laboratory and field experiments. The turbulent velocity and temperature scales, namely, u_* (friction velocity measured in m/s) and T_* (measured in K) are expressed through turbulent stresses (i.e. momentum and heat fluxes), τ and F , as

$$u_* = \sqrt{\tau}, \quad T_* = F/\sqrt{\tau}, \quad (3)$$

where τ and F are taken at sufficiently large distance from the surface, where they reach asymptotically constant values. The turbulent Prandtl number, Pr_t , is defined as

$$\text{Pr}_t = \frac{u_*}{T_*} \frac{dT}{dz} \left(\frac{dU}{dz} \right)^{-1} \quad (4)$$

The Obukhov turbulent length scale L (measured in m) is

$$L = \frac{u_*^2}{(g/T_0)T_*}, \quad (5)$$

where g is the gravitational acceleration and T_0 the reference temperature. (Note that our definition of the Obukhov length scale L , Eq. (5), does not include the von Karman constant, κ , whereas the popular version of this scale, \tilde{L} , includes κ in the denominator, so that $\tilde{L} = L/\kappa$. Then the second term on the right-hand side in brackets in Eqs. (1) and (2) becomes $C_U \frac{\eta}{\kappa \tilde{L}} = \tilde{C}_U \frac{\eta}{L}$ where $\tilde{C}_U = \frac{C_U}{\kappa} = 5$.)

Roughness lengths z_{0U} and $z_{0\Theta}$ in the case of an aerodynamically smooth flat surface are determined by conventional relations (e.g., [7])

$$z_{0U} = \frac{\nu}{u_*} \exp(-5\kappa), \quad (6)$$

$$z_{0\Theta} = \frac{\nu}{u_*} \exp(-2.5\kappa), \quad (7)$$

where ν is the kinematic viscosity of the air.

The bulk Reynolds and Richardson numbers are conventionally defined as

$$\text{Re} = \frac{U_0 \delta}{\nu}, \quad (8)$$

$$\text{Ri} = g \frac{\Delta T}{T_0} \frac{\delta}{U_0^2}. \quad (9)$$

Note that Eq. (1) does not give a direct answer to the question whether the air velocity will be enhanced or reduced, relative to bulk velocity, if the stratification strength (measured by the bulk Richardson number, Ri) is increased, since the turbulent stress (measured by the friction velocity) as well as the Obukhov length L both depend on the stratification strength.

3 Laboratory and Numerical Experiments

The laboratory experiment was performed in a Thermostratified wind-wave tank (TSWiWaT) of IAP over a smooth water surface (Figs. 1 and 2). Experiments were carried out for two cases: weakly stratified and strongly stratified air flow. In order to simulate stable temperature stratification of the air boundary layer, the input wind flow was heated before income but the temperature of the water surface remained unchanged. Thus in the weakly stratified case, the bulk temperature difference between air and water was about 4 K whereas in the strongly stratified case the temperature difference was about 20 K, and the wind bulk velocity was from 2 to 3 m/s in both cases. This setting of the laboratory experiment provides the bulk Reynolds and Richardson numbers in the range $Re \approx 40000$ – 60000 and $Ri \approx 0.01$ – 0.04 , respectively. The measurements of the air velocity in the working section at the distance of 7.5 m from the inlet were performed with the use of Pitot tubes at different heights above the water surface (Fig. 1). Hotwire installed together with Pitot tubes was used for simultaneous air temperature measurements. In order to reduce statistical errors an ensemble averaging was performed over five different experimental realizations.

PIV technique was applied for retrieving instantaneous wind velocity fields. $20\ \mu\text{m}$ polyamide seeding particles were injected in the flow at the first section of the channel (Fig. 2). Over the working section (with fetch 7.5 m) a continuous laser (1.5 Wt, 527 nm) was installed. Vertical laser sheet parallel to side walls of the channel was formed by a cylindrical lens. Motions of illuminated particles were recorded by a high-speed camera Videoscanner Videosprint (3012 fps, exposure time $100\ \mu\text{s}$, frame size $1280 \times 166\ \text{px}$ ($250 \times 32\ \text{mm}$), scale $195\ \mu\text{m}/\text{px}$). For each regime, 20 records were obtained, and each record has the duration of 0.5–2 s. Instantaneous velocity fields were retrieved by comparison of consequent frames with the use of a correlation postprocessing analysis where mean visible displacement of particles corresponded to shift peak of cross-correlation function. Calculations were carried for interrogation window of $64 \times 32\ \text{px}$ evenly distributed on a rectangular grid with 50% overlap. Sub-pixel interpolation of CCF peak position by three points was used. Due to high levels of peak-locking (since whole values of displacement were more probable to retrieve) comparison between neighbor frames provided wrong results for velocity fluctuations and turbulent fluxes. So each frame was compared to the frame separated by three, five, and seven frames after it. Using this method increased visible particle displacement and reduced peak-locking influence. The resulting profiles were similar for different frame distances. These velocity fields were filtered by difference between

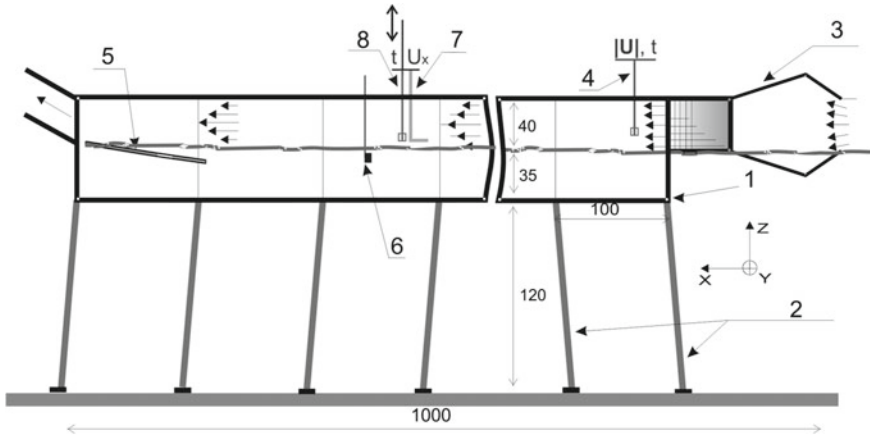


Fig. 1 Schematic of the laboratory experiment on the TSWiWaT (side view). All dimensions given in cm. 1—the wind channel 2—vertical beds 3—expanded-narrow section 4—hotwire controlling the incoming flow 5—wave damping beach 6—surface water temperature gauge 7—Pitot gauge installed on the scanning probe in the working section on the 8 m length from the income 8—hot wire installed together with Pitot

local velocity value and the median value at the given height. Mean velocity profiles were retrieved by averaging of the filtered velocity fields over time and horizontal coordinate. Mean velocity profiles were used for evaluation of the velocity fluctuation field which was also averaged in a similar way. By these means, the mean velocity and turbulent momentum flux profiles were retrieved for each record.

Direct numerical simulations of stably stratified Couette flow were performed at the same Re and Ri as in the laboratory experiment. The setup of the numerical experiment was similar to the one considered by Druzhinin et al. [5]. A Cartesian framework was considered where x -axis was oriented along the mean wind, z -axis is directed vertically upwards and y -axis was orthogonal to the mean flow. Periodical boundary conditions were considered in the x and y directions. The no-slip boundary conditions were prescribed at the top and bottom horizontal boundary planes separated by distance D and moving in the opposite directions along the x -axis with velocities $\pm 0.5 U_0$. The stable density stratification was specified by prescribing the air temperature at the bottom surface as $T = T_0$ and the top boundary plane as $T = T_0 + \Delta T$, where $\Delta T > 0$.

Numerical algorithm was based on the integration of full, 3D Navier–Stokes equations for incompressible fluid under the Boussinesq approximation [5]. The governing parameters in DNS were the bulk Reynolds and Richardson numbers defined as

$$Re = \frac{U_0 D}{\nu}, \quad (10)$$

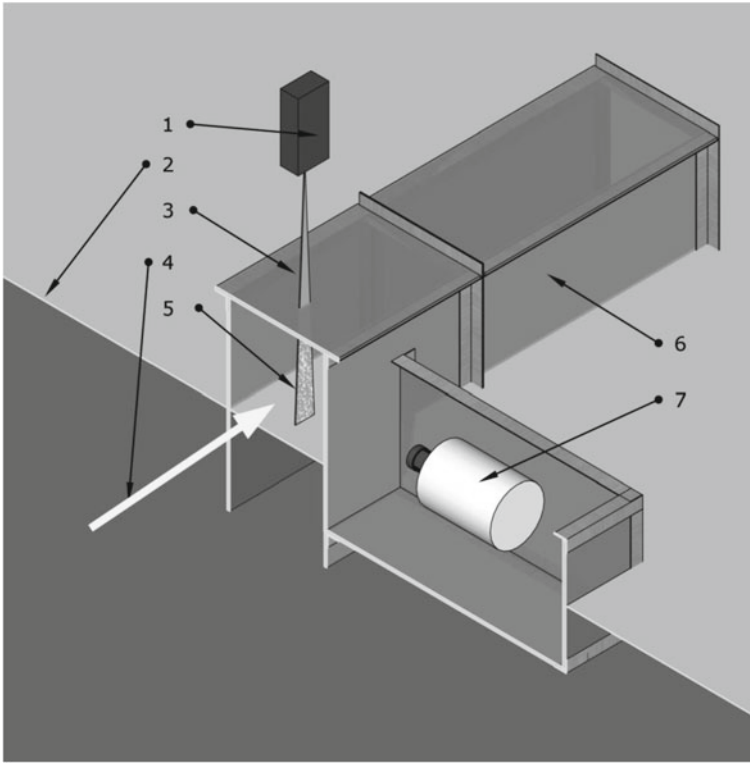


Fig. 2 Cross-wind section of the channel: 1—continuous laser; 2—water surface; 3—laser sheet; 4—wind direction; 5—PIV-particles; 6—underwater part of the channel; 7—high-speed camera in semi-submerged box

$$Ri = g \frac{\Delta T}{T_0} \frac{D}{U_0^2}. \tag{11}$$

In DNS we prescribed $Re = 40000$ and $Ri = 0$, in the non-stratified case, and $Ri = 0.04$, in the stratified case, which are in agreement with the parameters of the laboratory experiment. The organization of DNS procedure was similar to the one discussed by [5]. The velocity field in DNS was initialized as a weakly perturbed laminar Couette flow with the initial temperature deviation field put to zero. The integration was advanced in time until a statistically stationary flow regime was established. Then the sampling of the velocity and temperature fields was performed, and the mean vertical profiles of all fields were obtained by averaging over time and x and y coordinates.

Figure 3 compares mean velocity and temperature profiles obtained in the laboratory experiment and DNS. The figure also shows theoretically predicted profiles of mean velocity and temperature obtained with the use of Eqs. (1)–(5). Figure 3

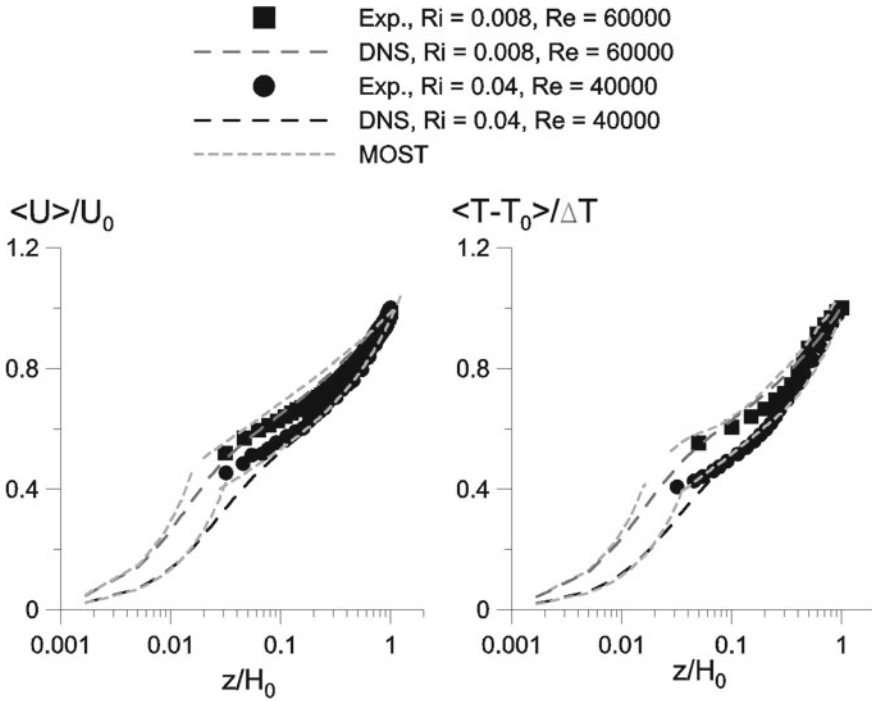


Fig. 3 Vertical mean velocity (left panel) and temperature (right panel) profiles in weakly- and strongly stratified boundary layer over smooth water surface obtained in laboratory experiment (symbols) and DNS (dashed curves). Theoretical predictions of MOST are in dotted line

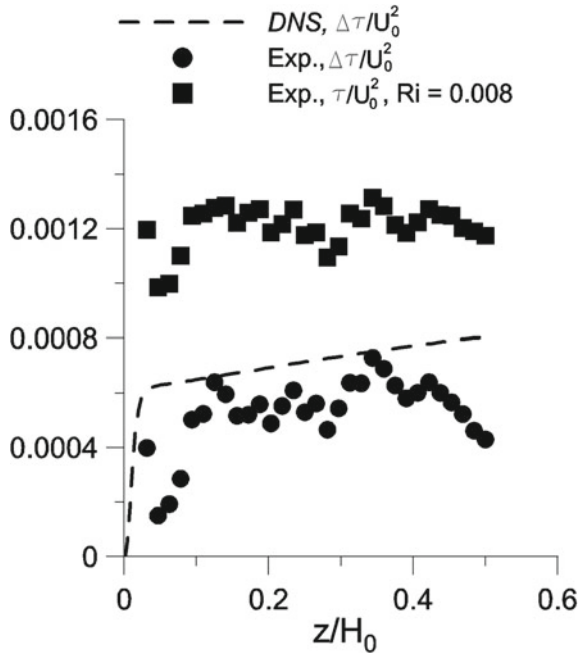
presents profiles of turbulent fluxes, τ and F , and turbulent Prandtl number, Pr_t , evaluated as described in (4), obtained in DNS. The experimental velocity profiles are normalized by the maximum (bulk) velocity $U_0 = U(z = H_0)$, approximately in the middle of the flume at height $z = H_0 \approx 24$ cm. The mean temperature profile was normalized with $T_0 = T(H_0)$. The DNS profiles are normalized by the mean velocity and temperature in the middle of the computational domain at $z = 0.5D$.

Figure 3 shows very good agreement between the experimental and numerical results and theoretical prediction. Note that the best agreement for the mean temperature profile was obtained for constant coefficient $C_T = 6$.

Note also that the flow in DNS is in statistically stationary turbulent regime according to characterization developed by Flores and Riley [6]. These authors compiled available laboratory and numerical data and performed DNS of their own to analyze the transition from turbulent to laminar regime in terms of the *turbulent Reynolds number*, Re_L , based on the Obukhov length scale and friction velocity

$$Re_L = \frac{Lu_*}{\kappa\nu}. \quad (12)$$

Fig. 4 Vertical profiles of turbulent momentum flux, normalized by the bulk velocity, τ/U_0^2 , obtained in the laboratory experiment in weakly stratified regime (squares), and the reduction of the momentum flux in the experiment and DNS (circles and dashed curve, respectively) under the strong stratification conditions



The basic result obtained by Flores and Riley [6] is that the stationary turbulent regime is maintained at $Re_L > 100$; otherwise turbulence degenerates and the flow becomes laminar. In our numerical experiment $u_* \approx 0.018U_0$ and $L \approx 0.37D$, so that $Re_L \approx 270$.

Figure 4 presents vertical profiles of turbulent momentum flux, normalized by the bulk velocity, τ/U_0^2 , obtained in the laboratory experiment in weakly stratified regime with $Ri \approx 0.01$ (squares), and the reduction of the momentum flux $\Delta\tau/U_0^2$ obtained in the experiment and DNS for bulk Richardson and Reynolds numbers $Ri \approx 0.04$ and $Re \approx 60000$ (circles and dashed curve, respectively). The figure shows a drastic reduction of turbulent momentum flux (by more than 50%) under the strong stratification regime.

4 Conclusions

We have performed laboratory experiment and direct numerical modeling of turbulent wind over water surface under stable stratification conditions. The laboratory and numerical experiments have been performed under the same bulk Reynolds and Richardson numbers which allowed a direct comparison between the measurements and calculations. Laboratory study and DNS considered both regimes of weak and strong stable stratification. Under the latter regime, the air–water temperature

difference created in the laboratory experiment was of up to 18 K and a relatively low wind speed of about 3 m/s which allowed us to reach a comparatively large bulk Richardson number (up to $Ri \approx 0.04$) and the corresponding bulk Reynolds number up to $Re \approx 60000$. Both contact (Pitot tube) and PIV methods were employed to measure the air velocity whereas the air temperature profile was measured simultaneously by a set of contact probes. The same bulk Ri and Re were prescribed in direct numerical simulation where turbulent Couette flow was considered as a model of the near water constant-stress atmospheric boundary layer.

Both experimental and DNS results show that mean velocity and temperature profiles obtained in our laboratory and numerical experiments agree well and also are well predicted by the Monin–Obukhov similarity theory. Although under strong stratification conditions a drastic reduction of both turbulent momentum and heat fluxes was observed, the prediction of MOST was still found to be a good approximation for the wind velocity and temperature profiles.

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