Investigation of the self-similarity of wind velocity and temperature profiles in laboratory modelling of the exchange processes in the atmosphere boundary layer

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Abstract. The paper is concerned with investigation of the self-similarity of wind velocity and temperature profiles in a stably stratified temperature turbulent boundary layer over the waved water surface.

1. Introduction
One of the central and most important problems of applied marine hydrometeorology and physical oceanography is investigation of exchange processes (fluxes of momentum, heat and moisture) in atmosphere boundary layer. Field observation of a turbulent airflow over a wavy water surface faces many difficulties in measuring characteristics of the wind flow and waves under severe wind condition of formation of steep and breaking waves. The good alternative is laboratory modelling of wind-wave interactions at the high-speed wind-wave channels. In such case, different methods may be applied for measuring fluxes in turbulent boundary layer. In [1] heat flux was obtained from direct eddy flux measurement and the profile method by hot film. But in case of strong wings and breaking waves spray droplets falling on the heated film, which leads to large measurement errors. In laboratory [2] experiment at strong winds the surface stress was determined from a momentum budget of sections of the tank. In [3] the same idea (measurement of the temperature differences between control sections) was applied for measuring heat fluxes. However, this is not direct method, errors are still significant and the data is contrary to the field observations. In [4] surface drag coefficient was directly received by profile method in case of hypothesis of the self-similarity of the airflow velocity profile in the wind-wave channel. The parameters of the waves in the experiment was determined by the wind speed only. This paper is devote to the generalization of the theory of self-similarity for the case of temperature profiles for a wide range of conditions (wind speed and surface waves).

2. The description of the experimental setup
The experiments were carried out in the Thermostratified Wind-Wave Tank (TSWiWaT) of IAP RAS. The detailed description of this experimental facility, the principles of creating and controlling the airflow is given in [4]. The general scheme of the experiments is shown in Figure 1. The airflow velocity at the axis of the channel is proportional to the fan frequency rotation $F$ (from 20 to 40 Hz) and varies from 8.8 m/s to 19 m/s, which corresponds to the equivalent speed (speed at height of 10 m) from 10 m/s to 35 m/s. To create the temperature stratification of the surface layer of the wind, the air
entering the channel was heated to 30-40 °C (depending on the airflow speed). The temperature on the water surface in all the experiments was maintained equal 15 °C.

**Figure 1.** General scheme of the experiment. (1) wind-wave channel body, (2) wind-wave bearings, (3) convergent – diffusion section with a honeycomb, (4) hot film anemometer at the entrance, (5) a net along the channel installed, (6) wave absorber, (7) Pitot tube on a scanning system, (8) hot film anemometer on the same scanning system, (9) three channel wire wave-gauge, (10) a gauge for water temperature measurements. The sizes are in cm.

The wave parameters in the flume were measured by three wire gauges positioned in the corners of an equal-side triangle with 2.5 cm side, and the data sampling rate was 100 Hz. Three-dimensional space-time spectra were obtained from the measured data by the algorithm FDM [4].

A special feature of this experiment is the control of the surface waves regardless on the wind flow velocity in the channel. For this purpose, a plastic net of 0.25 mm thickness with a cell of 1.6 x 1.6 mm were stretched along the entire channel. The net did not affect the heat exchange, but the characteristics of surface waves varied depending on its depth (Figure 2): the waves were absent when the net was located at the level of the undisturbed water surface, but at maximum depth (33cm) it had practically no effect on the parameters of the disturbances for all wind speeds in the facility.

**Figure 2.** Significant wave height dependent on the net depth.
Velocity and temperature profiles in the working section of the flume (at a distance of 6.5 m from the entrance channel) were measured simultaneously with the help of the Pitot tube and hot film gauge, mounted on the vertical scanner. The L-shaped Pitot tube with the differential pressure transducer Baratron MKS 226 A provided the accuracy of velocity measurement equal to 3 cm/s. The accuracy of temperature measurements with hot film is 0.1 °C. The scanning method with the consecutive height increment of 3-5 mm and measurement time of 2 minutes at each point was used. For each fixed wind speed and net depth two profiles of velocity and temperature were measured for subsequent averaging. The lower level of scanning was at a distance of 1 cm from the crests of the waves and depended on the wind speed, while the upper layer was 38 cm (2 cm below the upper lid of the channel). The temperature and wind speed at the inlet of the flume were controlled with the additional hot film gauge. The temperature gauge was placed under water in the working section to measure the temperature of the surface layer of water.

3. The self-similar behavior of the velocity and temperature defect profiles
To determine the parameters of the atmosphere boundary layer the algorithm that proposed in [4] was used to generalize the model of the boundary layer near a flat surface [5]. In this work the self-similar behavior of the velocity defect profiles in the near-wall turbulent flows was studied, and following expression was proposed:

\[ \frac{U_{\text{max}} - U(z)}{u_*} = F\left(\frac{z}{\delta}\right), \tag{1} \]

where \( U_{\text{max}} \) is the maximum speed in a turbulent boundary layer, \( u_* \) is the wind friction velocity and \( \delta \) is the boundary layer thickness.

According to [5] for non-gradient turbulent boundary layer at a flat plate or in the tube, the following approximation of the self-similar velocity profile were made:

\[ U_{\text{max}} - U(z) = \begin{cases} u_*\left(\frac{1}{\kappa} \ln\left(\frac{z}{\delta}\right) + \alpha\right) & ; z/\delta < 0.15, \\ \beta u_* \left(1 - \frac{z}{\delta}\right)^{\frac{1}{\beta}} & ; z/\delta > 0.15. \end{cases} \tag{2} \]

where \( \kappa = 0.4 \) is the Karman constant.

The constants \( \alpha \) and \( \beta \) can be obtained using the best fit to the experimental data. In [5], the values of the constants (\( \alpha = 1, \beta = 9.6 \)) for non-gradient turbulent boundary layer and (\( \alpha = 1, \beta = 7.1 \)) for the turbulent Poiseuille flow in a pipe are presented. The results of previous experiments [4] in the wind-wave flume show that the profile of the velocity defect in the airflow above the waved water surface is also self-similar, and the velocity profile can be approximated by the expression (2). Determining the constants \( \alpha \) and \( \beta \) included the following data processing. The profiles of the flow velocity defect measured at a certain frequency of rotation of the fan and for the different net positions, were expressed in terms of self-similar coordinate \( y = z/\delta \) and normalized by the curvature of the velocity profile \( \beta u_* \). Obtained dimensionless velocity defect profiles are shown in Figure 3 for a number of fan rotation frequencies. It can be seen that the experimental points for a fixed speed and set of net positions (different surface waves) converge on certain curves, confirming the self-similarity of the profile of the flow velocity defect in the channel above the water surface.

With this normalization the logarithmic part of the self-similar profile of the velocity defect has the form:

\[ \frac{U_{\text{max}} - U(z)}{\beta u_*} = \frac{1}{\beta} \left(\frac{1}{\kappa} \ln\left(y\right) + \alpha\right) \tag{3} \]
Taking into account (1), it is easy to determine the constants $\alpha$ and $\beta$ from the logarithmic best fitting of the experimental points. A certain difference between the fit of the curves near the water surface can be seen from Figure 3e.

**Figure 3.** Dimensionless velocity defect profiles for the following values of the fan speed: (a) – 20 Hz, (b) – 30 Hz, (c) – 35 Hz, (d) – 40 Hz, (e) – all symbols in the same graph.

**Figure 4.** Dependences of the constants $\alpha$ and $\beta$ on the fan speed.

The dependence of the constants $\alpha$ and $\beta$ on the fan speed is shown in Figure 4. A slight change in the constants is statistically significant within the 95% confidence intervals shown in the figure. Dependences of $\alpha$ and $\beta$ on fan speed with increasing wind speed are similar to each other.

Similar processing carried out with the temperature profiles allows determining the Stanton number and temperature roughness from the temperature profiles in the channel. We used in this case the self-similarity of the profile of the temperature defect, which was defined similar to the expression (1) for the velocity defect:

$$\frac{T_{\text{max}} - T(z)}{T_c} = G\left(\frac{z}{\delta_T}\right),$$

where

$$T_c = \frac{\langle T'w' \rangle}{u_c}$$

(4)

(5)
To approximate the self-similar dependence for the profile of the temperature defect we used the expression similar to (2):

$$T_{\text{max}} - T(z) = \begin{cases} T_{*}\left(\frac{1}{\kappa} Pr_t \ln\left(z / \delta_T\right) + \alpha_T\right) ; & z / \delta_T < 0.15, \\ \beta_T z \left(1 - z / \delta_T\right)^2 ; & z / \delta_T > 0.15. \end{cases} \quad (6)$$

For implementation the profiling method of measurements of turbulent heat flux in atmosphere boundary layer we need the turbulent Prandtl number $Pr_t$. According to [6] $Pr_t$ was assumed to be 0.85. This value was also confirmed by direct numerical simulation of turbulent boundary layer above the wavy water surface [7]. To determine the constants $\alpha_T$ and $\beta_T$ data processing were carried out for the velocity profile (see above). Similarly, the profiles of the temperature defect of the airflow were expressed in terms of the self-similar coordinate $y = z / \delta_T$ and normalized by the curvature of the temperature profile $\beta_T T_z$. Obtained dimensionless profiles of the temperature defect are shown in Figure 5 for various fan rotation frequencies and net positions.

Figure 5. Dimensionless profiles of the temperature defect for the following values of the fan speed: (a) – 20 Hz, (b) – 30, (c) – 35 Hz, (d) – 40 Hz, e – all symbols in the same graph.

The dependences of the constants $\alpha_T$ and $\beta_T$ on the rotational speed of the fan are shown in Figure 6, where there is no statistically significant change in the constants within 95% confidence intervals, with $\alpha_T = 2.8$, $\beta_T = 9.5$. It differs from velocity profiles with constants that show a significant dependence on wind speed.
Conclusion
A series of experiments to study the self-similarity of the temperature and velocity profiles in a stably stratified temperature turbulent boundary layer over the waved water surface was carried out at the wind-wave stratified flume of IAP RAS. Simultaneous measurements of the airflow velocity and temperature were obtained in a wide range of wind speed and characteristics of the surface waves.

It was demonstrated that the profiles of the velocity defect and the temperature defect of the turbulent airflow at the near water surface are self-similar. Besides, for both velocity and temperature the form of self-similarity profiles (parameters $\alpha$, $\beta$, $\alpha_T$, $\beta_T$) does not depend on parameters of surface roughness, but only on the wind speed.

The constants $\alpha$, $\beta$, $\alpha_T$, $\beta_T$ were obtained from the best fit of the experimental data. Calculated dependences of constants demonstrate different behavior: significant dependence on wind speed in case of the velocity, and no dependence on the temperature (within 95% confidence intervals). These data will be used for obtaining parameters of the wind flow including momentum and heat fluxes.

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