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Drag Coefficients in Light Wind*

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Abstract

Recent developments of observational techniques have enabled us to measure wind velocities down to the extremely low wind speed region. The present authors have made turbulent flux measurements near the surface in various conditions and found that the surface drag coefficient increases with decreasing wind speed in the low wind speed region below a few meters per second without regard to the stability. The inflection occurs at higher wind speed than expected in transition from smooth flow. The detailed analysis suggests that this may be caused by the residual turbulence by local temperature fluctuation under calm conditions.

1. Introduction

The knowledge of the surface drag coefficient is one of the most fundamental pieces of information in the studies of the atmospheric boundary layer. It has been known that the drag coefficient of the earth surface is almost constant irrespective of wind speed in the moderate and high wind speed regions. However, in the low and extremely high wind speed regions, it has been discussed little owing to difficulties in accurate measurements of Reynolds stress and wind speed. Recent developments in the observational technics, such as a sonic anemometer-thermometer, have enabled us to obtain more accurate data in various wind conditions. The present authors have been making intensive studies on the turbulent exchanges in the atmospheric boundary layer with the sonic anemometer-thermometer, and have found that the drag coefficient increases with decreasing wind speed in the low wind speed region. The details are shown in the present paper.

2. Observational Data

All of the data used in the present study are summarized in Table 1. The observations at Shionomisaki in 1969 and 1972 were made at the same place over the flat ground but the surface vegetations were different. Biwako and Kasumigaura are the first and second largest lakes in Japan and the measurements were made on the masts over shallow water near the coast, 20 and 40m from the shore line during

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Table 1. List of Observations

Site	Year	Surface	Height (m)	Number of Runs	Reference
Shionomisaki	1969	bare soil	1.5	56	3)
Kasumigaura	1970	shallow water	1.5	28	4)
Oklahoma	1971	short grass	40	173	5)
Shionomisaki	1972	short grass	1.9	48	6)
Biwako	1972	shallow water	5.6	165	7)
East China Sea	1974	open ocean	18	26	8)

periods of onshore wind. The observations in Oklahoma were made on the WKY TV-Tower in the suburbs of Oklahoma City. The ground around the tower is slightly undulating and covered with short grass.

The Reynolds stress or momentum flux, M, was obtained by the eddy correlation method shown by the following equation;

$$M=-\rho\ \overline{u'w'} \tag{1}$$

where ρ is density of air, and u and w are the horizontal and vertical wind velocity components. The wind velocity components were measured by a sonic anemometer-thermometer with 20cm sound paths (Mitsuta[1]) installed on the tower. The computations of covariances were made by a hybrid-analog computer, HYSAT (Hanafusa[2]), over the sampling period of 30min in most cases. The drag coefficient, at the height of measurement, C_{Dz}, is defined as;

$$C_{Dz}=M/\rho\bar{U}_z^2=-\overline{u'w'}/\bar{U}_z^2 \tag{2}$$

where $\bar{U}_z$ is the magnitude of the vector mean wind at the height of measurement, z.

3. Drag Coefficient as a Function of Wind Speed

In order to compare the values of the drag coefficients of various observing heights, all of the observed data were adjusted to the values at the height of 10m from the surface, assuming the logarithmic profile of wind speed by the following relations neglecting the effects of atmospheric stabilities;

$$\bar{U}_{10}=\bar{U}_z+(u_*/k)\ln(10/z) \tag{3}$$

$$C_{D10}=\{k/(\ln(10/z)+k/(C_{Dz})^{1/2}\}^2 \tag{4}$$

where $u_*=(-\overline{u'w'})^{1/2}$ and k is the Karman constant (0.4 being assumed in this study).

The adjusted drag coefficients over the shallow inland water surface are shown in Fig. 1 as a function of wind speed at 10m. Even though the points are scattered fairly widely, it is clear that the drag coefficient has a dependency on wind speed.

In the high wind speed region ($\bar{U}_{10}\geq 5$m/sec), the drag coefficient is almost constant and is nearly equal to 1.7×10^{-3}. This value is a little larger than the value obtained over the ocean. In the low wind speed region, the drag coefficient apparently

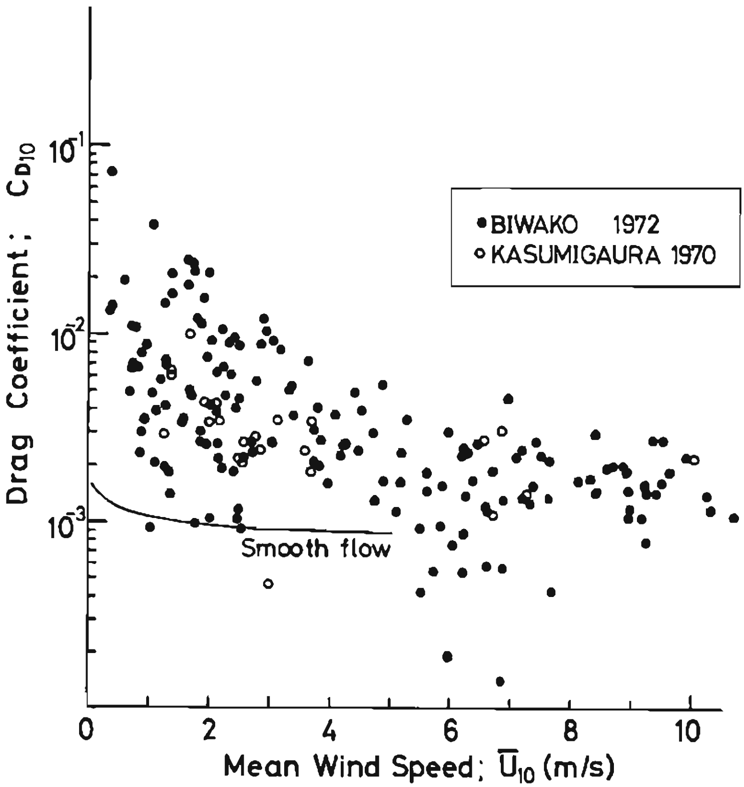

Fig. 1. Drag coefficients as a function of wind speed at 10 m as observed over the shallow inland water surface. A solid line shows the drag coefficient of aerodynamic smooth surface.

increases with decreasing wind speed and the inflection point is at about 4m/sec.

The adjusted drag coefficients over land surface are shown in Fig. 2. Even though the points are scattered widely, a tendency of the drag coefficient to increase in the low wind speed region is clearly seen. However, the inflection point is lower than the case over water and is about 1m/sec. Above this inflection point, the drag coefficient seem to be irrespective of wind speed. The averaged values for three cases are 14.5×10^{-3} for Oklahoma over slightly undulating grass land, 10.5×10^{-3} for Shionomisaki covered with grass land (1972), and 5.5×10^{-3} for Shionomisaki bare soil case (1969).

4. Discussions

When the surface is relatively smooth and/or wind speed is low, the value of the eddy viscosity near the surface may decrease and become of the same magnitude as the kinematic viscosity of air, ν. In that case, the wind profile is no longer independent from viscosity but can be expressed as follows;

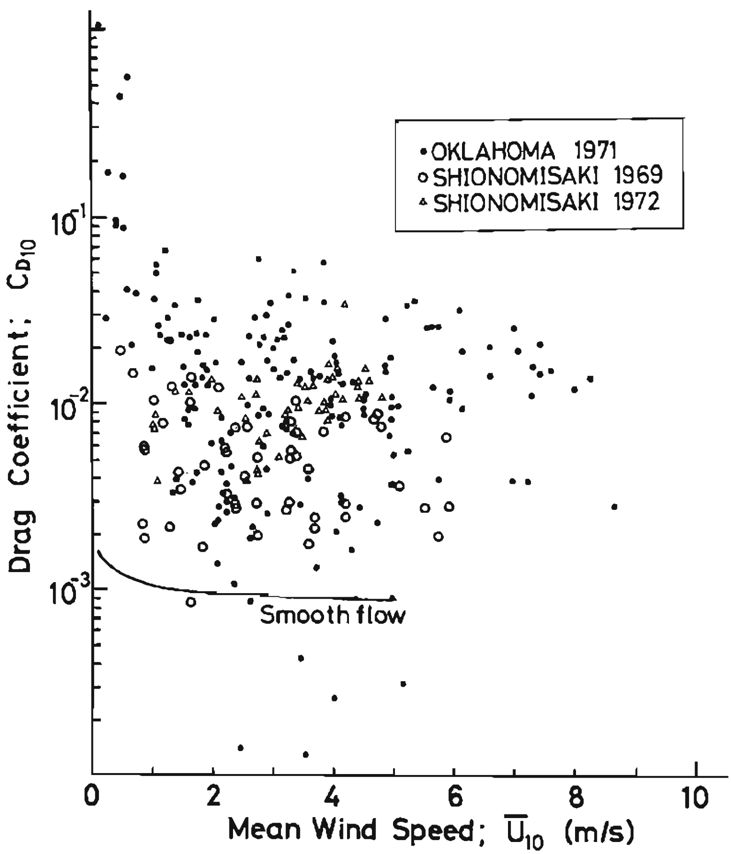

Fig. 2. Same as Fig. 1 but for over land.

$$\bar{U}_z/u_* = \frac{1}{k}\ln(u_* z/\nu) + A \tag{5}$$

where A is a constant and is approximated by 5.5 after Nikuradse[9]. If the flow state is aerodynamically smooth as expressed in this equation, the drag coefficient is not a constant but a function of wind speed, and this relationship is expressed as follows;

$$C_{Dz}^{-1/2} = \frac{1}{k}\ln(R_z(C_{Dz})^{1/2}) + A \tag{6}$$

where $R_z = \bar{U}_z z/\nu$. The variation of the drag coefficient with wind speed in this case is shown in Figs. 1 and 2 as the solid line. The computed drag coefficient with eq.(6) increases with decreasing wind speed. However, as is clearly seen in these figures, the observed drag coefficients are much larger than the computed ones assuming aerodynamically smooth flow and also the observed inflection points appear at higher wind speeds than the computed ones. Therefore, the observational results are not well explained by transient into aerodynamically smooth flow.

In the above discussions, the effects of atmospheric stability have been neglected.

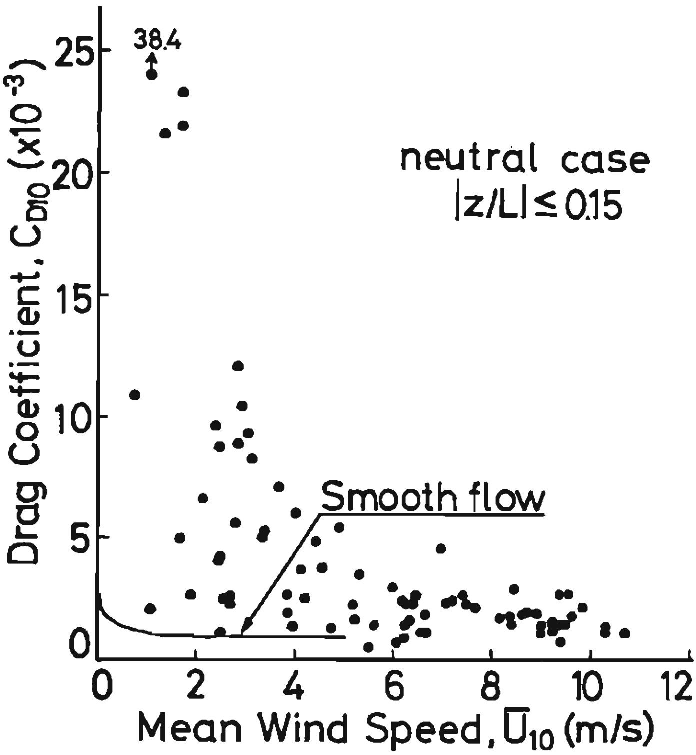

Fig. 3. Neutral drag coefficient as a function of wind speed at 10 m as observed over the shallow inland water surface (Biwako, 1972).

Deardorff[10] has studied on this point and introduced semi-empirical relations between the drag coefficient and the equivalent neutral drag coefficient. According to his results the non-neutral correction factor is fairly large. Therefore, this may be a cause of scattering of the data points in Figs. 1 and 2.

To see the more detailed nature of the drag coefficient, the data of neutral stability conditions ($|z/L| \leq 0.15$) were selected from the data of Biwako, 1972. There are 80 neutral cases, which are shown in Fig. 3. The neutral drag coefficient over a shallow water surface (adjusted for 10m) shown in this figure increases with decreasing wind speed in the range lower than 4m/sec in the same tendency as Fig. 1. The averaged value of neutral drag coefficient over shallow water is 1.87×10^{-3} in the wind speed range higher than 5m/sec (adjusted for 10m). The observed inflection point is much higher than expected in the case of aerodynamically smooth flow.

The neutral drag coefficients obtained over open ocean, near the center of the East China sea, are shown in Fig. 4. These data were quoted from the results[8] of direct observation of turbulent fluxes on the mast of R.V. Keifu-Maru during the AMTEX. As the observation was made over warm current in winter, atmospheric stratification was unstable in most cases. All of the observed momentum fluxes were

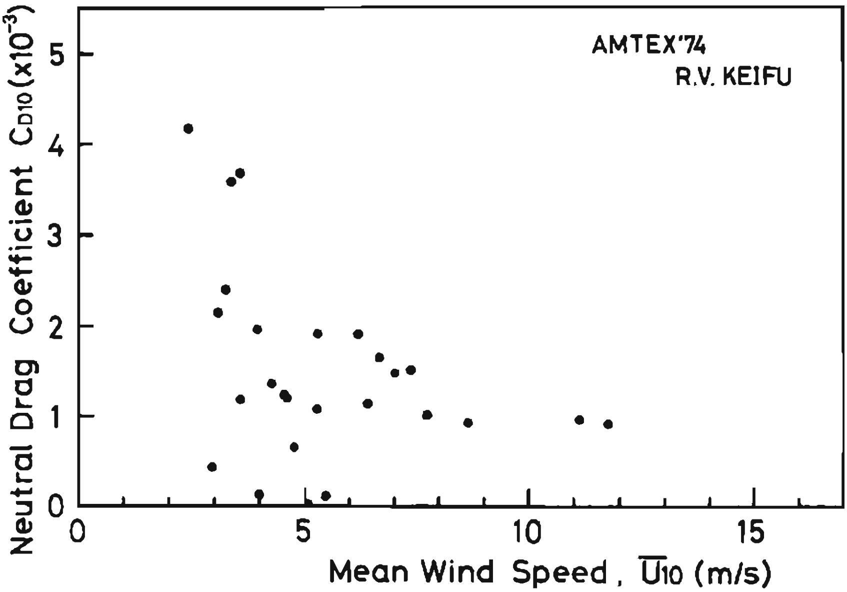

Fig. 4. Neutral drag coefficients as a function of wind speed at 10 m as observed over the East China Sea during AMTEX '74 (after Fujitani and Mitsuta[8]).

adjusted using flux-to-profile relationship to obtain neutral drag coefficients. The method of adjustment is the same as the one used by the present authors[11]. The open ocean drag coefficients shown in Fig. 4 are a little smaller than those over shallow water shown in Fig. 3. This might be caused by smaller fetch over the water surface in the case over shallow water. However, on the whole, the tendency to increase in low wind speed region is clearly seen and the inflection point is also the same.

The drag coefficient can be rewritten as;

$$C_{Dz}=(-\overline{u'w'})/\overline{U}_z^2=C_{uw}(\sigma_u/\overline{U}_z)(\sigma_w/\overline{U}_z) \quad (7)$$

where C_{uw} is the correlation coefficient of u and w, and σ_u and σ_w are the standard deviations of u and w components. Dependencies of three parameters of the right hand side of Eq.(7) on wind speed for the data shown in Fig. 3 are shown in Fig. 5.

As is clear from this figure, intensities of turbulence (σ_u/U_z and σ_w/U_z) are constant in the wind speed range greater than 3 or 5m/sec (the averaged values being 0.25 and 0.035 respectively) but increase at the lower wind speed ends. This means that wind turbulence does not die down even if wind speed tends to zero and mechanical turbulence disappears. The remaining turbulence in the calm condition must be of thermal origin caused by fluctuations of local air temperature in spite of neutral stability on the average. This hypothesis is supported by the fact that the standard deviation of air temperature, shown at the top of Fig. 5, does not decrease with wind speed but even increases at the low wind speed end even in the neutral

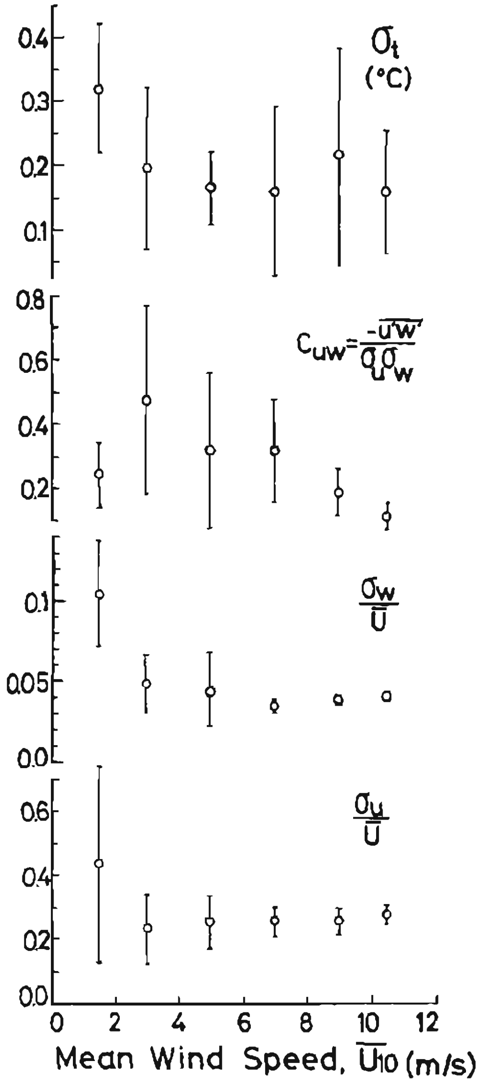

Fig. 5. The standard deviation of temperature, the correlation coefficient between u and w, intensity of turbulence of the vertical component and that of horizontal component from the top to the bottom as functions of wind speed at 10 m (Biwako, 1972).

stability. While, the correlation coefficient shows a broad peak at about 3m/sec and the value at the lowest end is almost the same as that in higher wind speed range.

5. Conclusive Remark

The drag coefficient increases with decreasing wind speed in the lowest wind speed region caused by remaining turbulence and Reynolds stress can be written in the following form even in neutral conditions;

$$(K_m+K_0)\ \partial u/\partial z=u_*^2 \qquad (8)$$

where K_m is a turbulent transfer coefficient of momentum assumed as $K_m=ku_*z$ and K_0 is viscosity caused by the background fluctuations of temperature in the neutral stability and is larger than kinematic viscosity. K_0 may be a function of height and the threshold of mechanical turbulence will be easily seen at the higher altitude.

6. Additional Examples

The same situation that the drag coefficient increases with decreasing wind speed in the low wind speed region can be seen in other cases than the present ones. For example, the wall drag coefficient of air flow in a tunnel shows remarkably large value at low air speeds such as 0.5 to 1 m/sec (Hiramatsu et al.[12]). The recent experiment on the drag force on a structure in natural wind also indicates that the drag coefficient of a lattice structure in natural wind increase with decreasing wind speed at about 6m/sec and is three times as large at the speed of 2m/sec.

References

1) Mitsuta, Y.: Sonic anemometer-Thermometer for Atmospheric Turbulence Measurements, Flow, Its Measurement and Control in Science and Industry, Vol. I, Instrument Society of America, Pittsburgh, 1974, pp. 341-347.
2) Hanafusa, T.: New Hybrid Analog Data Acquisition System for Atmospheric Turbulence (HYSAT), Special Contributions of Geophysical Institute, Kyoto University, No. 11, 1971, pp. 47-56.
3) Fujitani, T., T. Hanafusa, and Y. Mitsuta: Measurement of Eddy Momentum Flux near the Ground, Special Contributions of Geophysical Institute, Kyoto University, No. 10, 1970, pp. 85-91.
4) Hanafusa, T.: Some Aspects of Turbulent Fluxes near the Ground, Special Contributions of Geophysical Institute, Kyoto University, No. 11, 1971, pp. 57-70.
5) Hanafusa, T. and Y. Mitsuta: Structure of the Planetary Boundary Layer in High Winds Observed from a 0.5km TV Tower, Wind Effects on Structures, Ed. by H. Ishizaki and A. Chiu, Univ. Tokyo Press, 1974, pp. 69-78.
6) Mitsuta, Y., T. Hanafusa, O. Tsukamoto and H. Kawanishi: A Study of Energy Budget at the Air-Ground Interface, Bulletin of Disaster Prevention Research Institute, Kyoto University, Vol. 22, No. 209, 1973, pp. 249-257.
7) Mitsuta, Y., T. Hanafusa, N. Monji, O. Tsukamoto and T. Hayashi: Measurement of Turbulent Fluxes over a Lake Surface, Contributions of Geophysical Institute, Kyoto University, No. 13, 1973, pp. 35-52.
8) Fujitani, T. and Y. Mitsuta: Direct Measurement of Turbulent Fluxes on R. V. Keifu-Maru during AMTEX '74, (to be published).
9) Nikuradse, J.: Strömungs Gesetze in rauhen Röhren, Verhandl. deut. Ing. Forsch., No. 361, 1933.
10) Deardorff, J. W.: Dependence of Air-Sea Transfer Coefficients on Bulk Stability, Journal of Geophysical Research, Vol. 73, 1968, pp. 2549-2557.
11) Mitsuta, Y., N. Monji and O. Tsukamoto: Bulk Transfer Coefficients as Observed during AMTEX, Paper presented at the IAGA/IAMAP Joint Assembly at Seattle, 1977.
12) Hiramatsu, Y., Y. Mitsuta and F. Honda: Natural Ventilation of the Mountain Road Tunnel, Proceedings of the First International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels, British Hydromechanics Research Association, pp. DI-1-12.