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## The Molecular Temperature Boundary Layer of the Atmosphere Over Various Surfaces

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With 1 Figure

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### Summary

The author, after giving a general description of the molecular temperature boundary layer of the atmosphere, shows that this is almost invariably present over water surfaces and even over sand surfaces, so that these may be considered to be aerodynamically smooth surfaces. For the thickness of the molecular temperature boundary layer over water surfaces, parametrization relations are given in dependence upon the friction velocity and the effects of waves. Over oil-covered water surfaces, the sensible heat flux is, in general, greatly reduced within the molecular temperature boundary layer.

### Zusammenfassung

#### Die molekulare Temperaturgrenzschicht der Atmosphäre über verschiedene Oberflächen

Ausgehend von allgemeinen Betrachtungen zur molekularen Temperaturgrenzschicht der Atmosphäre wird gezeigt, daß diese über Wasserflächen und sogar über Sandflächen nahezu ständig vorhanden ist, diese also als aerodynamisch glatte Oberflächen zu betrachten sind. Für die Dicke der molekularen Temperaturgrenzschicht über Wasserflächen werden Parametrisierungsbeziehungen in Abhängigkeit von der Schubspannungsgeschwindigkeit und dem Welleneinfluß mitgeteilt. Über ölbedeckten Wasserflächen tritt eine wesentliche Minderung des fühlbaren Wärmestromes durch die molekulare Temperaturgrenzschicht ein.

### 1. Introduction

The atmospheric boundary layer is that part of the atmosphere in which increases as height above surface level and where changes of the wind direction can be observed as high above the earth as the geostrophic wind of the free atmosphere. These phenomena are caused by the decrease in friction,

i. e., the increase in the Reynolds number. The processes of exchange taking place in this connection being of a predominantly turbulent nature. It is only in the immediate vicinity of the surface that molecular conductions and diffusion processes will be assuming considerable importance at magn  $Re \sim 1$ . Accordingly, the atmospheric boundary layer may be subdivided as follows:

*Molecular boundary layer* (laminar stream boundary layer) which is characterized by purely molecular exchange processes and which is about 1 millimeter thick;

*viscous buffer layer* which is characterized by molecular as well as turbulent exchange processes and which is about 1 centimeter thick, the molecular boundary and viscous buffer layers together constituting the *viscous sub-layer*;

*dynamic sublayer* which is about 1 meter thick and which is characterized by vanishing stability dependence because of  $z < L$  according to the Monin-Obukhov similarity theory (where  $z$  is the height and  $L$  is the Monin-Obukhov-length);

*Prandtl's layer* which is characterized by turbulent exchange processes and of which the upper limit is between 20 and 50 meters because of a deviation from the quasi-constancy of energy exchange, which is as high as 10 to 20 per cent;

*Ekman's layer* which is the layer where most of the wind direction change can be observed to occur and of which the upper limit, i. e., the edge of the atmospheric boundary layer, is between about 500 and 1500 meters.

The studies reported by the author in the present paper were made to investigate those layers which are immediately adjacent to the surface and, more specifically, the molecular boundary layer. It has not so far been possible, because of the problems associated with measurements made in nature, to demonstrate experimentally the "laminar" stream boundary layer and molecular diffusion boundary layer for water vapor in the atmosphere. The only data that are presently available are those which were derived from measurements made by Hinzpeter and Lobemeyer [12] and Clauss et al. [2] as well as from extensive studies made by Foken et al. [8, 9, 10, 11, 13] to investigate the molecular temperature boundary layer, for which use had been made of a high-resolution temperature sonde ("Fallsonde" measuring system according to Foken [5]).

## 2. The Molecular Temperature Boundary Layer of the Atmosphere

If stationarity is assumed and advective processes are neglected, then the general heat conduction equation will, for the range of small Reynolds numbers (magn  $Re \sim 1$ ), show the height-dependence of temperature in the

region of the molecular temperature boundary layer to be

$$\frac{\partial^2 T}{\partial z^2} = 0 \quad (1)$$

where  $T$  is the temperature (see [15]). Solving this equation through the use of similarity theory the following relation:

$$T = \frac{H \cdot z}{\nu_T \cdot \rho \cdot c_p} \quad (2)$$

where  $\nu_T$  is the thermal conductivity,  $\rho$  is the density of air,  $c_p$  is the specific heat, and  $H$  is the sensible heat flux. Within this layer the sensible heat flux is constant with the height. Thus, a completely linear temperature gradient is obtained for the molecular temperature boundary layer. Following from laboratory measurements made on a smooth wall by Žukauskas and Šlančjauskas [19] is, for the thickness of the molecular temperature boundary layer,

$$\delta_T = 7 \cdot \frac{\nu}{u_*} \quad (3)$$

where  $\nu$  is the kinematic viscosity and  $u_*$  is the friction velocity. In nature, a relation that is far more complex than that is given above (3) must be assumed, namely,

$$\delta_T = f(\nu, \nu_T, u_*, g/T, H_t, h_s, \zeta) \quad (4)$$

where  $g$  is the gravitational acceleration,  $h_s$  is the average height of roughness elements,  $H_t$  is the sensible and latent heat flux, and  $\zeta$  is the wave phase parameter.

Compared with methods of measurement in the turbulent layer, the importance of the molecular temperature boundary layer lies in the possibility of independently determining the sensible heat flux according to

$$H_\delta = \lambda \cdot (\partial T / \partial z) \quad (5)$$

(where  $H_\delta$  is the sensible heat flux determined by measurements made in the molecular temperature boundary layer and  $\lambda$  is the molecular heat conductivity) and in the thickness of the molecular boundary layer, which is suitable as a boundary condition for various problems. However, a major disadvantage in this connection is that the "laminar" stream boundary layer thickness,  $\delta$ , is of much greater interest and that the relation between  $\delta$  and  $\delta_T$ , which exists in nature, is still very insufficiently known. If van Driest's proposition [4] for a smooth wall is used, then

$$\delta / \delta_T = Pr^{1/2} \text{ air } 0.85 \quad (6)$$

(where  $Pr$  is the Prandtl number) will be obtained.

In the following, the behavior of the molecular temperature boundary layer is discussed, for different surfaces, by reference to experimental data.

### 3. Structure of the Molecular Temperature Boundary Layer in Dependence Upon the Surface

#### 3.1 Water Surface

Heretofore, the majority of studies of the molecular temperature boundary layer have been performed over water surfaces, with results of more than 400 measurements made in this layer being presently available. Of these, 14 were made in the Kieler Bucht [12], 38 on the Atlantic Ocean [2], 178 on the Caspian Sea, and 186 in the near-shore zone of the Baltic Sea (near Zingst, G.D.R.). This is a remarkable number of measurements, especially in view of the difficulty of the operation of measuring. Chundžua and Andreev [1] also succeeded in demonstrating the existence of the molecular temperature boundary layer within the Black Sea's water surface. All of the previous measurements provided definite information on both the existence and structure of the molecular temperature boundary layer. Results of previous measurements encouraged Foken and Kuznecov [10, 11] to make additional measurements on the Caspian Sea, by which it was possible to gather much information especially about the influence of waves on boundary layer thickness. The measurement results showed that it is, in general, possible for eq. (4) to be greatly simplified. It is only in the case of  $u_* \rightarrow 0$  that there will be free convection and that terms  $g/T$  and  $H_t$  will have a certain influence. Under such conditions, the records no longer allow the existence of a molecular boundary layer to be clearly demonstrated. Rather, the profile indicates a layered structure which Foken and Kuznecov [10] interpret as suggesting phenomena of convective replacement. Roughness elements ( $h_s$ ) were not found to be effective in the region being investigated. The measurements made for friction velocities up to and including  $u_* \sim 60$  cm/s all show the existence of a molecular boundary layer, an exception being those measurements which were made over oil-covered water surfaces (see section 3.3) and under conditions of heavy vertical motion of the water surface, which did not permit the principle of measurement described by Foken [5] to be used. Some measurements made by Hinzpeter and Lobmeyer [12] may also be interpreted as reflecting the conditions referred to above.

The measurements made in nature were identical to those made under laboratory conditions up to friction velocities of  $u_* \sim 20$  cm/s. This is the range which is characterized by short gravitational waves and swell. For high friction velocities, i. e., stronger wind waves, it is possible for an influence exerted by waves to be observed. According to [11], the boundary

between the two cases may be very accurately expressed by the dimensionless height of roughness,  $\sigma_\eta \cdot u_* / \nu$ , where  $\sigma_\eta$  is the dispersion of elongation of the water surface in the frequency range  $f > 1$  Hz. The limit value obtained is  $\sigma_\eta \cdot u_* / \nu = 300$ . The influence exerted by waves is evident from the fact that the molecular temperature boundary layer measured on the downwind side of the wave is thicker by a factor of 3 than that which is measured on the upwind side of the wave. This is considered to be due primarily to a lower friction velocity on the downwind side. The thickness of the molecular temperature boundary layer obtained on the upwind side,  $\delta_T = (7.4 \pm 3.7) \nu / u_*$ , is identical with the results of laboratory measurements. Accordingly, it may be assumed that there is no increase in friction velocity on the upwind side and that the average value of  $u_*$  for the entire wave is half that measured at a height of about 6 meters (flux-measurements). The constant flux layer theory cannot, therefore, be applied to that layer which is immediately adjacent to the water surface.

There are several relations which may be used to determine  $\delta_T$ .

a)  $\delta_T = (6.0 \pm 3.5) \nu / u_*$  for  $\sigma_\eta \cdot u_* / \nu < 300$  ( $u_* < 20 \dots 30$  cm/s) and upwind side values of  $\sigma_\eta \cdot u_* / \nu > 300$ .

b)  $\delta_T = 7.5 \frac{\nu}{u_*} (2 + \sin(\xi - \pi/2))$  for  $\sigma_\eta \cdot u_* / \nu > 300$  with accurate wave phase assignment (assumption of an idealized wave:  $\xi = 0$  on the upwind side,  $\xi = \pi$  on the downwind side).

c)  $\bar{\delta}_T = 13 \nu / u_*$  for  $\sigma_\eta \cdot u_* / \nu > 300$ , mean value for the entire wave

$$(\bar{\delta}_T = \int_0^{2\pi} \delta_T(\xi) d\xi).$$

The above equations may be used as parametrization relations for the thickness of the molecular temperature boundary layer.

### 3.2 Sand Surface

In the summer of 1976, seven measurements of the molecular temperature boundary layer over the sand surface were made near Zingst, G.D.R., in the near-shore zone of the Baltic Sea. A tube was placed in the ground, of which the opening was covered with paper and, subsequently, with a thin layer of sand having an average grain size of 0.2 . . . 0.4 millimeters. The surface temperature of this layer of sand was the same as the surrounding sand temperature. The test profile, which had a height of several meters, was scanned, all the way to the tube, by the "Fallsonde" (the velocity of fall of which was 1 m/s) recording the temperature between the upper end of the test profile and the sand surface. All of these measurements gave the same general results (Fig. 1) in that they indicated a linear temperature gradient in the molecular temperature boundary layer, an abrupt transition to the buffer layer with a

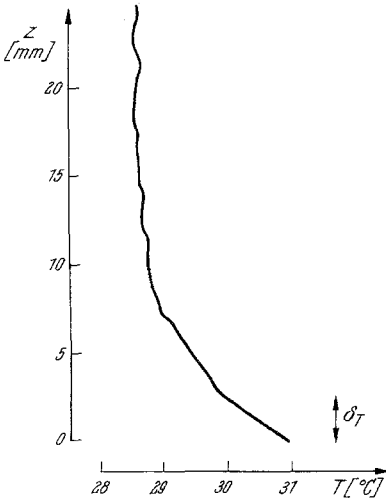


Fig. 1. Measurement of air temperature directly over a sand surface (Zingst; July 1, 1976 – 11:45 hrs.; wind velocity at a height of 6 meters: 4.7 m/s)

nonlinear but still relatively large gradient, and the layer above them is characterized by full turbulence.

According to Foken [6], comparisons made between the results of measurements performed over sand and water surfaces and those of laboratory measurements made on a smooth wall showed that, in the region of the molecular temperature boundary layer, there are no differences between measurements made in the laboratory and in nature and that differences may be observed only in the upper part of the buffer layer. Measurements of the molecular temperature boundary layer over water surfaces have demonstrated quite clearly that an aerodynamically smooth surface ( $\delta_T < h_s$ ) is invariably present on the sea, an exception being, of course, full storms (foam-covered water surface). This is in agreement with an assumption made by Roth [16] on the basis of a determination of the roughness parameter,  $z_0$ , from wind profile data. However, the statement made above may be extended to include sand surfaces as well as surfaces with less conspicuous geometric roughness structures (such as, for example, concrete and very short grass).

### 3.3 Oil-Covered Water Surface

Temperature measurements made over oil-covered water surfaces or films of oil, respectively, do not indicate the existence of a molecular temperature boundary layer. Rather, it has been possible for a layer, of which the vertical extension above the sea is from a few millimeters to centimeters, to be deter-

mined which is characterized by isothermal conditions or a negligible temperature gradient, respectively, which cannot be measured with a sufficient degree of accuracy. This indicates a considerable decrease in exchange of heat and may be considered to be in agreement with the measurement in the turbulent layer, by Kuznecov and Panin [14], of a 1.5-fold and five-fold reduction of the drag coefficient and  $z_0$ , respectively, over oil films. However, it is quite possible that the "Toms"-effect may be responsible for this quasi-isothermal layer. However, this assumption is of a purely hypothetical nature, for it should be extremely difficult for this effect (and the conditions that must exist before the effect can occur) to be demonstrated experimentally. The "Toms"-effect is the reduction in friction on walls due to polymers added to liquids which are capable of flowing. According to Debrule and Sabersky [3], this effect tends to reduce drag coefficient and the coefficient of heat exchange by a factor of 3 and 5, respectively. If polymers should also be present in the layer of the air above the film of oil, then this could be a cause of the "nonexistence" of a molecular temperature boundary layer, which, however, would have to be attributed to a considerable increase in thickness.

#### 4. Conclusions

The investigations reported in this paper show that aerodynamically smooth surfaces and, therefore, a molecular temperature boundary layer or stream boundary layer, respectively, are not as rare an occurrence as has heretofore been generally believed. Sverdrup's classical energy exchange models [17, 18] are again assuming considerable importance since the constants required for them have been determined by these measurements. However, what is quite problematic in connection with such models is, according to [7], the inadequate modelling of the buffer layer. On the other hand, results presented by Foken and Kuznecov [11] show that the constant-flux-layer-theory, upon which such models are based, is not satisfied, at least under near-neutral conditions, in the air layer which is immediately adjacent to the water surface. However, the most important results of these investigations should be the parametrization relations for determining the thickness of the molecular boundary layer, which may be used for roughness studies and boundary conditions.

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## References

1. Chundžua, G. G., and E. G. Andreev: Eksperimental'nye issledovanija teploobmena meždu morem i atmosferoj pri melkomasšabnom vzaimodejstvii. *Izv. AN SSSR, Fiz. atmosf. okeana*, 10, 1110–1113 (1974).
2. Clauss, E., H. Hinzpeter, and J. Müller-Gleve: Ergebnisse von Messungen des Temperaturfeldes der Atmosphäre nahe der Grenzfläche Ozean-Atmosphäre. "Meteor"-Forsch.-Ergebnisse, Reihe B, No. 5, 85–89 (1970).
3. Debrule, P. M., and R. H. Sabersky: Heat Transfer and Friction Coefficients in Smooth and Rough Tubes With Dilute Polymer Solutions. *Intern. J. Heat & Mass Transfer*, 17, 529–540 (1974).
4. Driest, E. R., van: Convective Heat Transfer in Gases. In: *High Speed Aerodynamics and Jet Propulsion* (Lin, C. C., ed.), Vol. 5: Turbulent Flows and Heat Transfer, p. 339–427. Princeton 1959.
5. Foken, Th.: Die Messung der Mikrostruktur der vertikalen Lufttemperaturverteilung in unmittelbarer Nähe der Grenze zwischen Wasser und Atmosphäre. *Z. Meteor.*, 25, 292–295 (1975).
6. Foken, Th.: Zur Temperaturstruktur an einer glatten Wand und einer aerodynamisch glatten Oberfläche. *Z. angew. Math. Mech.* (In print.)
7. Foken, Th.: Kritische Bemerkungen zu Energieaustauschmodellen mit der molekularen Grenzschicht der Atmosphäre. *Z. Meteor.* (In print.)
8. Foken, Th., P. Hupfer, and G. N. Panin: The Behaviour of the Laminar Boundary Layer of the Atmosphere in the Near-Shore Zone Above the Sea. *Raporty MIR, Seria R, No. 1a*, 231–238 (1975).
9. Foken, Th., O. A. Kuznecov, and G. N. Panin: Comparison of Heat Flow Measurements Between Sea and Air With Different Direct Measuring Methods. *Raporty MIR, Seria R, No. 1a*, 139–243 (1975).
10. Foken, Th., and O. A. Kuznecov: Beitrag zur Struktur der molekularen Temperaturgrenzschicht der Atmosphäre über dem Meer. *Gerlands Beitr. Geophys.*, 86, 191–203 (1977).
11. Foken, Th., and O. A. Kuznecov: Die wichtigsten Ergebnisse der gemeinsamen Expedition KASPEX-76 des Institutes für Ozeanologie Moskau und der Karl-Marx-Universität Leipzig. *Beitr. Meereskunde*, H. 41 (1978).
12. Hinzpeter, H., and P. Lobmeyer: Versuche zum Nachweis laminarer Grenzschichten über dem Meer. *Ann. Meteor. N.F.*, 4, 15–18 (1969).
13. Hupfer, P., Th. Foken, and G. N. Panin: Existence and Structure of the Laminar Boundary-Layer of the Atmosphere in the Near-Shore Zone of the Sea. *IAMAP, Report of Proc. First special Assembly, Melbourne, Australia, IAMAP Publication, No. 15a*, 134 (1974). (See also: *Z. Meteor.*, 25, 94–102 (1975).
14. Kuznecov, O. A., and G. N. Panin: O vlijanie neftjanoj plenki na poverchnosti morja na turbulentnost' na privodnom sloe atmosfery. *Meteor. Gidrol.*, No. 5, 97–99 (1974).
15. Landau, L. D., and E. M. Lifschitz: *Lehrbuch der Theoretischen Physik, Bd. VI: Hydrodynamik*, 618 pp. Berlin: Akademie-Verlag, 1974.
16. Roth, R.: Modelle für das Windprofil über einer rauhen und einer glatten Oberfläche. *Beitr. Phys. Atmosph.*, 45, 277–304 (1972).



17. Sverdrup, H. U.: Das Maritime Verdunstungsproblem. *Ann. Hydrogr. Marit. Meteor.*, 64, 41–47 (1936).
18. Sverdrup, H. U.: On the Evaporation from the Ocean. *J. Marine Res.*, 1, 3–14 (1937/38).
19. Žukauskas, A., and A. Šlančjauskas: Teploodača v turbulentnom potoke židkosti, *Teplofizika* 5, 327 pp., Vil'njus: Izd. "Mintis", 1973.

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