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Atmospheric Thermal Stratification and the Position of Mechanical Ventilation Air Intakes

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The specific characteristics of the thermal structure in the atmospheric surface layer can be utilized for thermal optimization of ventilation of buildings. General description of these characteristics, as well as procedures for their evaluations are presented. Illustrative observations are given, which imply that thermal energy gains can be obtained under appropriate ventilation procedures. The applicability and significance of the suggested procedures are discussed.

NOMENCLATURE

C_p	air specific heat, $J \cdot kg^{-1} \cdot K^{-1}$
g	gravity acceleration, m s^{-1}
k_0	the Von Karman constant (=0.35)
L	the Monin–Obukhov length, m
T	the air temperature, K
T^*	the surface buoyancy temperature scale, K
T_0	the surface temperature, K
z	height, m
z_0	the surface roughness parameter (about 0.15 of the obstacles height in the upwind direction), m
ρ_a	air density, kg m^{-3}

1. INTRODUCTION

TYPICALLY, following sunset under clear skies, an air temperature inversion (i.e. increase of air temperature with height) is likely to be established within the lowest several tens of metres above the ground, as a result of net long-wave radiative cooling at the surface with the cessation of solar insolation. Figure 1a provides a schematic illustration of vertical temperature profiles within an inversion. The intensity of the nocturnal surface inversion tends to be enhanced in valleys as well as within small-scale terrain depressions where turbulent vertical mixing is reduced. As the ground is heated by solar radiation during the daytime hours, usually a thermally unstable surface layer is established (i.e. the temperature vertical gradient dT/dz is $\leqslant -1°C/100$ m). Figure 1b provides a schematic illustration of the thermal structure of the surface layer during daytime hours.

These general thermal characteristics of the surface layer which are most typical over bare soils, may be modified considerably under specific ground situations as will be discussed in this paper. The general thermal characteristics of the atmospheric surface layer suggests that the temperature of air vented into buildings is likely to be effected significantly by the elevation of the air inlet.

In many large buildings maintaining internal circulation heating/cooling (as industrial complexes, hospitals, shopping centers, office buildings, public halls, hotels, etc.), considerable ventilation may be needed. The amount of the air ventilation is dependent mostly on the number of the occupants in the building or on types of indoor activities which produce odors or gases which are not permitted to exceed given thresholds (e.g. [1] and [2]). The present ASHRAE minimum ventilation rate is 5 cfm (cubic feet per minute) of outdoor air per person; however, it has recently been recommended to be raised to 15 cfm per person [3]. Some building codes may require much higher ventilation rates. Ventilation may result in the need for significant additional thermal energy in order to maintain the appropriate heating/cooling in the building. Apparently no systematic study is reported in the literature evaluating the significance of atmospheric surface-layer thermal stratification in the context of the minimization of thermal energy losses due to ventilation. The present paper provides an initial evaluation of this aspect and indicates the potential gains in thermal energy likely under optimized ventilation. These evaluations can also be used in consideration of optimized air inlet height for: (i) evaporative cooling systems which are used in warm and dry geographical locations; (ii) cooling of building by means of an external air circulation; (iii) night ventilation—the potential use of outside air to cool a building at night, which has been shown to reduce cooling energy for buildings with significant mass [4].

Procedures for evaluating the surface-layer thermal structure are outlined briefly. Observational evaluations and quantification of various general thermal stratification characteristics of the atmospheric surface-layer, are presented. Specific characteristics which are pertinent to various practical aspects of ventilation thermal optimization are outlined. Generally, a suburban or rural environment is considered in this study, since in the urban environment the vertical temperature gradients within the atmospheric surface layer may be suppressed sig-

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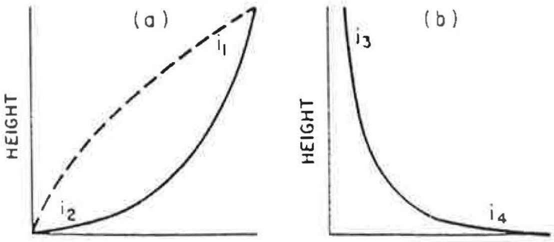

Fig. 1. Schematic illustration of typical vertical profile of temperature during: (a) clear sky nocturnal period (solid line—profile during light wind conditions; dashed line—profile during moderate and strong wind conditions); (b) clear sky daytime period. Optimized air inlets relative elevation above ground for the winter nocturnal period and snow covered ground are indicated by i_1; for summer nocturnal period, i_2; for summer clear sky daytime period, i_3; for winter clear sky daytime period, i_4.

nificantly by the high surface roughness and the thermal effects of the surface.

2. DETERMINATION OF THE SURFACE-LAYER TEMPERATURE STRUCTURE

General aspects

For purposes involving optimized air intake, climatological features of the surface-layer thermal structure for a specific site should be established. Archives of detailed observations of vertical profiles of temperature are relatively few and are generally limited in the period of measurement. Radiosonde temperature profiles, which are obtained from routine meteorological observations by the various meteorological services are stored in well organized archives. However, these profiles consist of relatively coarse vertical resolution near the surface. Careful examination of these data by a surface-layer meteorologist, as related to a given region, should result in an initial bulk estimation of the surface-layer thermal stratification. Selective short periods of observations at a given site using a portable meteorological tower would provide detailed information relating to the local surface layer thermal characteristics.

Modelling

The general characteristics of the vertical temperature profile within the surface layer for bulk evaluation can be obtained through analytical model approximations applied to the lower atmosphere, e.g. [5]. However, a more practical and accurate approach utilizes atmospheric numerical model, e.g. [6]. Applying such a model involves a solution of a set of prognostic equations for several relevant atmospheric variables within the lower atmosphere, including an equation for the temperature. Selected representative initial atmospheric conditions of typical seasonal atmospheric situations can be established. Numerical model simulations using these initial conditions are likely to provide a general insight into the surface-layer annual temperature climatology at a given site. The computer CPU time needed for such simulations when one dimensional model versions are used is small, even when a PC is used.

Parameterization

Based on surface-layer observations, parameterization for the general temperature profiles within the surface layer have been reported in various studies. The relations from [7] are commonly used, in which the temperature at height z above the ground is given by:

$$T_z = T_0 + \frac{T^*}{k_0}\left[0.74\left(\ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L}\right)\right)\right] - \frac{gz}{C_p} \quad (1)$$

For detailed definitions of L and the ψ function the reader is referred to [7]. For our purpose, when the surface temperature, and temperature at a height z above the ground, are known, as well as the wind speed at that level, the values of T^* and L can be computed and vertical profiles of T are determined (for a given situation T^* and L are approximately constant within the surface layer). It can be shown, e.g. [8] and [9], that these quantities can be evaluated by having measurement of temperature in any two levels and wind speed in one level.

3. OBSERVATIONS

An example of the frequency of occurrence of nocturnal inversions, as well as illustrative observed temperature profiles within the atmospheric surface layer in the non-urban environment, is provided in the following. The temperature profiles were selected quite randomly from various data sets in different geographical locations.

Nocturnal period—flat terrain

During the nocturnal period in the summer, in most subtropical and midlatitude geographical locations, building cooling needs are usual, in contrast to heating needs during the winter nights. The onset of the nocturnal surface temperature inversion following sunset is a very rapid process, e.g. [10]. Following a period of a few hours from sunset, the surface temperature inversion usually can be considered as quasi-steady for the rest of the night. The depth of the nocturnal surface temperature inversion is typically ~ 100 m with the largest temperature vertical gradient in the lowest few tens of metres. Its development is most significant under clear sky, light wind and dry atmosphere conditions. According to the statistics provided by [11], (based on radiosonde observations) nocturnal surface temperature inversions are frequent throughout most of the United States. Figure 2 provides the frequency of the winter and summer nocturnal surface temperature inversions constrained by $dT/dz > 1.15°/100$ m, as based on [11]. Since the temperature vertical gradients were established in that study using radiosonde measurements, their magnitude near the surface are likely to be in general considerably underestimated. In addition, as the measurements were taken at sites with typical distance of about 300 km apart, these data are unrepresentative for local modifications in the thermal stratification due to specific terrain characteristics. However, Fig. 2 should be indicative of the relative frequency of conditions conducive to the formation of intense nocturnal surface temperature inversions, and their distribution, in the U.S. Illustrative nocturnal temperature profiles based on relatively refined measurements within the nocturnal surface layer are pro-

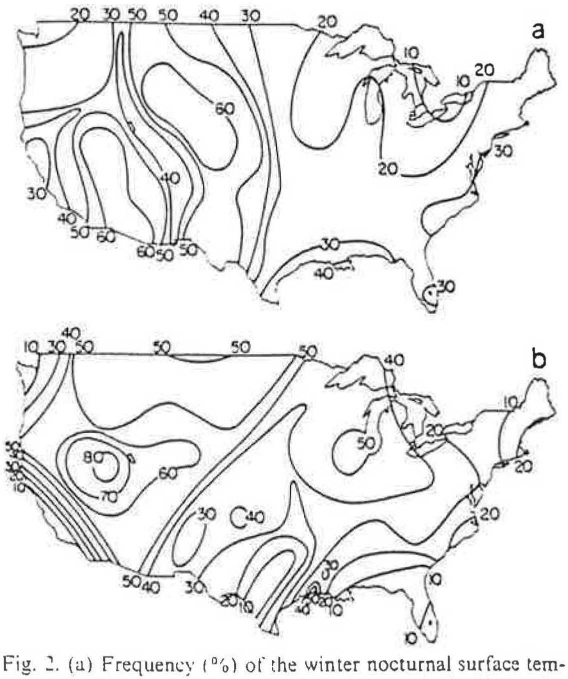

Fig. 2. (a) Frequency (%) of the winter nocturnal surface temperature inversion with $dT/dz > 1.15°C/100$ m in the U.S.A. (b) Frequency (%) of the summer nocturnal surface temperature inversion with $dT/dz > 1.15°C/100$ m in the U.S.A. (based on Figs 50 and 52 in [11]).

vided in Fig. 3. Generally, they indicate that ΔT values within the range of several °C within the surface layer, are typical at these specific sites.

In conclusion, air intake during the winter nights at least several metres above the ground would optimize heating/cooling thermal energy usage (i_1; Fig. 1a). The air intake during the summer nights should preferably be as close as possible to the ground (i_2; Fig. 1a). It is worth noting that the temperature inversion structure of the nocturnal surface layer is considered in frost protection in winter crop areas. Wind machines are used in radiative frost situations to generate vertical mixing within surface layer to increase near ground air temperature, e.g. [12].

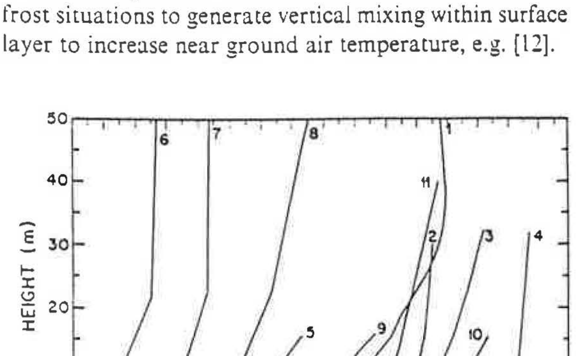

Fig. 3. Observed nocturnal vertical profiles of temperature within the surface layer. (#1) from [17], Cobb mountain, CA, September, 1980; (#2-4) From [18], Sublette, KS, July 1968 [profile #4 is during strong wind conditions]; (#5) from [19], Denilguin, N.S.W., Australia, October, 1976; (#6-8) From the NOAA meteorological Tower, Boulder, CO, February, 1987; (#9-10) from [20], O'niell, NE, September, 1953; (#11) from [21], Matimba, South Africa, August, 1985.

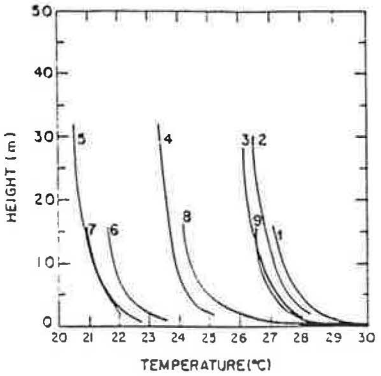

Fig. 4. Illustrative observed daytime vertical profiles of temperature within the surface layer. (#1) From [22], Kerang, Australia, February, 1968; (#2-5) From [18], Sublette, KS, July, 1968; (#6-7) From [19], October, 1976; (#8-9) from [20], O'niell, NE, September, 1953.

Nocturnal period—complex terrain

In valleys, drainage flows commonly develop during the nights. At the bottom of the valley convergence of drainage flows causes reduction in flow speed and consequently suppresses the vertical turbulence, resulting in enhanced effectiveness of the surface layer radiative cooling. Thus, in bottoms of valleys, the nocturnal surface temperature inversions are likely to intensify, increasing the potential for thermal optimization of ventilation. A study by [13], for example, provides observations of the intensity of nocturnal temperature inversions in valley terrain in Colorado during the early morning hours, indicating a temperature inversion of several °C. Likewise, small-size terrain depressions (i.e. tens to hundreds of metres in horizontal extent) cause nocturnal accumulation of noticeably cooler air than in a flat terrain surrounding, e.g. [10] and [14].

Daytime period

Assuming a relatively clear sky and low near-surface wind speed, a thermally unstable surface layer is usually generated during the daytime hours with the largest vertical temperature gradients within 1–2 m above the ground; the magnitude of dT/dz is further enhanced by dry ground conditions, during the summer in warm regions. It can be shown that near the surface $(dT/dz) \propto z^{-1}$ [22]. Above this layer the vertical temperature gradient reduces at the rate of 1–2°C/100 m. Qualitatively similar features are observed in the winter, however, the magnitude of the temperature vertical gradient is smaller. Several illustrative temperature profiles observed during daytime are shown in Fig. 4. Based on these profile features it is suggested that during the summer daylight hours, air intakes several metres above ground would avoid the intake of near-surface warm air (i_3; Fig. 1b). During the winter, using an inlet as close as possible/to the ground (i_4; Fig. 1b) would lead to increased intake of warmer air.

4. SPECIFIC SURFACE CONDITIONS

In the previous evaluations, situations were considered in which bare soil conditions are typical. In the following, we outline some potentially significant deviations from

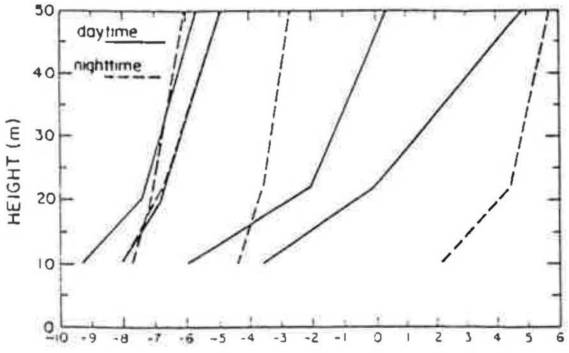

Fig. 5. Illustrative observed vertical profiles of temperatures over snow covered ground. From the NOAA Meteorological Tower, Boulder, CO. Winter 1986-87.

these surface conditions and their impact on the aforementioned evaluations. In the following two cases it is assumed that significant large areas (i.e. not less than several tens of km^2) acquire the specified surface conditions.

Wet soil/vegetated areas

Highly wet bare soil (as in areas affected frequently by precipitation or in irrigated areas) tends to reduce the intensity of the daytime surface-layer thermal instability. In addition, it causes a reduction in the nocturnal surface temperature inversion intensity as : (a) generally wet soil thermal conductivity is relatively high, e.g. [15], and therefore the increased surface soil thermal flux moderates the surface temperature cooling; (b) the related increase of atmospheric moisture reduces the net radiative cooling at the surface. Short vegetation (not under water stress) has a similar impact on the surface-layer thermal structure. In a forest canopy during the daytime the in-canopy air temperature near the ground may be lower by several °C than the temperature above the canopy crown; similar differences exist during the nocturnal period, e.g. [10]. Therefore for buildings within dense tall forest, summer ventilation is optimized by setting the air intake near the ground. During winter the optimal position is above the canopy crown.

Snow cover

Snow cover over densely populated areas during a significant portion of the winter is common in northern mid-latitudes. As the reflectivity of solar radiation from snow surfaces is frequently very high (e.g. [16]) persistent deep and intense surface temperature inversion are a frequent feature during daytime, as well as nighttime, hours. Furthermore, since snow surface temperature cannot exceed 0°C, large-scale advection of warmer air over snow surface induces surface temperature inversions. Cold Arctic air masses which occasionally penetrate to those latitudes acquire a stable near-surface thermal stratification, which is maintained over snow cover. Figure 5 provides several selected daytime observations of temperature profiles over snow cover (measurements are unavailable in the lower 10 m where temperature inversions are likely to be relatively intense in many cases). It is suggested that in regions with high snow frequency, the optimized air inlet position should be at least several metres above surface (i_1; Fig. 1a and i_3; Fig. 1b).

5. CONCLUSION

The specific thermal structure of the atmospheric surface layer provides on many occasions opportunities for reducing the thermal energy losses involved with ventilation of buildings in which internal recirculation cooling/heating systems are installed. The present paper has described the general surface-layer thermal characteristics as well as provided some illustrative observational examples implying on the potential gains in thermal optimization of ventilation. Various constraints (including: technical, economical, design, air quality conditions and effects involving wind flow around buildings, mostly when the wind is not light) may be involved with the application of such optimization, and therefore it might be unjustified in all situations. Also in some locations (e.g. within the center of urban areas) the surface-layer vertical temperature gradients are likely to be insignificant, and thus inappropriate for the optimization of ventilation. However, it is suggested that optimization may be yet potentially beneficial in many situations. In addition, surface-layer thermal characteristics can be considered for cooling enhancement when evaporative cooling systems are implemented in buildings, or in buildings in which air ventilation is used for cooling purposes during the warm season.

Based on the evaluations provided in the previous sections, it is suggested, that in some situations an option for ventable lower and upper level air intake is needed in order to provide the capability for ventilation thermal optimization. In these situations devising a dual option of the air intake/air outlet can be considered. Outdoor temperature sensors could be implemented near the air intakes in order to control their optimal utilization. Even if it is not feasible to consider an option for two levels of air intakes, yet an optimized single inlet height above ground (at ground level or building roof or any intermediate height) can be determined based on the annual thermal characteristics of the surface layer in the specific area. On the other hand, in large buildings in which several air intakes are installed, optimization of their heights can be determined based on the specific cooling/heating requirement of the building.

Finally, for illustrative purposes, we assume that the surface-layer thermal characteristics prevailing enable a gain ΔT (warmer/lower) under optimum air inlet position for air which is vented at the rate of V m^3 s^{-1}. The related thermal energy gain, ΔE, is:

$$\Delta E = \rho_a C_p \cdot V \Delta T, \qquad (2)$$

where ρ_a ($\cong 1.2$ kg m^{-3}) is the air density. Then, for $V = 1$ m^3 s^{-1} (e.g. a building with a few hundred occupants) and a moderate value of $\Delta T = 2.5$°C the thermal energy gain is at least $\Delta E \cong 3000$ W. Without optimization, this amount of energy would be provided by the heating/cooling system (in practice, a larger amount of energy will be consumed by the system, since the conversion efficiency of the system is obviously lower than 100%). In large industrial plants the required ventilation rates may be substantially larger, and therefore, the potential thermal energy saving may increase considerably.

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