INFLUENCE OF PLANT CANOPY ON THE KATABATIC WINDS

Zhiwen Luo and Yuguo Li[1]

Department of Mechanical Engineering, The University of Hong Kong, Hong Kong, China

Abstract

Katatatic winds are important in pollutants transportation and ventilation for urban settlements in mountainous regions. Most of the theoretical analysis of slope flow is confined on bare slope, although the mountains are covered by heterogeneous forest canopies. To fill this gap, a new theoretical model for slope flow by taking the forest canopy into account was developed in this paper. Classical Prandtl slope flow model is implemented above the canopy while the canopy flow model is applied within the uniform canopy. The coupling of the two models is formulated at the canopy top. The influence of atmospheric stability and slope inclination is also investigated.

Key words: slope winds, tree canopies, urban ventilation

1. INTRODUCTION

Many serious urban pollution episodes occur at the condition of weak or absent background winds. For a city located in mountainous regions, when there are no background winds, locally thermally-driven flow will play its role. During the day time, the upslope/anabatic flow can be developed while in the night time, the flow will be downslope (katabatic) which is corresponding to the heating or cooling of the slope surfaces. At this time, the pure thermally-driven slope flow is very crucial and beneficial in ventilating the urban area nearby (Kitada, Okamura, & Tanaka, 1998; Ohashi & Kida, 2002).

The origin of the theoretical solutions of the katabatic winds can trace back to Prandtl's model in 1942(Pandtl, 1942). He derived a simple one-dimensional model to describe the thermally driven flow on the slope with the assumptions that the slope is infinite in length, the perturbation of the potential temperature on the slope surface is uniform along the slope, the Coriolis effect is neglected, and nonlinear advective effects are ignored. However, Prandtl's model is restricted in the case of smooth slope surface without considering the effect of the vegetative canopies. The presence of the vegetation canopies can exerts resistance on the flow within it. Few authors considered the slope cover e.g. grass, bushes, and trees, on the katabatic flow. Bergen (1969) probably was the first to document cold air drainage flow within vegetation. He measured the vertical profiles of wind speed and temperature, and developed relationships between wind speed and the potential temperature drop along the slope. Yi et al (2005) proposed a model incorporating the buoyancy term in a canopy model to examine the influence of the nocturnal drainage flow on CO_2 exchanges between vegetation and atmosphere. As a matter of fact, the thermally driven slope winds not only can occur within the canopy but also can be developed above the canopy (Komatsu, et al., 2003). It is our major purpose in this study to develop a theoretical model taking into account both the above and within canopy katabatic winds.

2. MATHEMATICAL MODELS

2.1 Flow within homogeneous canopies

The turbulent flow in vegetative canopies has been extensively studied since the very early 1960s. Excellent reviews on this issue can be found in Finnigan (2000) and Raupach and Thom (1981). To study the spatially averaged time-mean turbulent canopy flow, double-averaging method is often applied. We consider the simplest case: one-dimensional motion in horizontally homogeneous canopies, no static pressure gradient, advection, and steady-state. As shown in Fig.1, we assume a slope with an infinite length inclined at an angle of α which everywhere has a definite excess of temperature over the stratified mass of air. The Cartesian coordinate system is set as s in the direction of along the slope surface, and n normal to the slope, the origin is located at the canopy top. The canopy height is h. The governing equations for katabatic canopy flow can be written as follows:

$$\frac{\partial \overline{u'w'}}{\partial n} = g\beta\Delta\theta\sin\alpha + c_D a\bar{u}^2(n) \tag{1}$$

Where, Δθ is the deficit of the potential temperature in the drainage flow which is assumed to be a constant. This assumption indicates a well-mixing condition within the canopy which is rather rational and widely observed in real

[1] Liyg@hku.hk

canopies (Devito & Miller, 1983). Drag coefficient c_D and leaf area density a (frontal area per unit volume) is taken as constant here to represent uniform canopies.

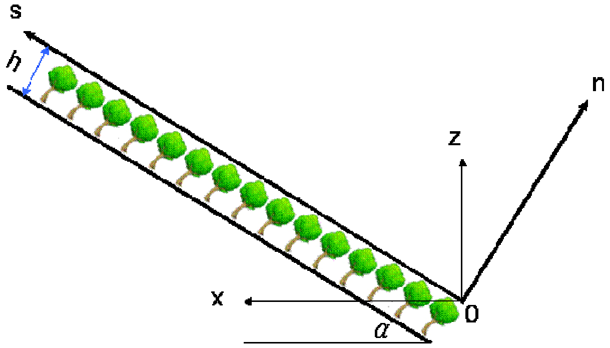

Figure 1. Schematic diagram for slope flow model on a forest slope

The spatial-averaged Reynolds stress $\overline{u'w'}$ can be parameterized by a simple relationship proposed by Yi (2008). He postulated a local equilibrium existing between the rate of horizontal momentum transfer and its rate of loss due to drag at an arbitrary level of z.

$$\tau(z)/\rho = -\overline{u'w'}(z) = c_D(z)\overline{u}^2(z) \tag{2}$$

Then Eq.(1) can be rewritten as

$$\frac{\partial(c_D\overline{u}^2(n))}{\partial n} = g\beta\Delta\theta\sin\alpha + c_D a\overline{u}^2(n) \tag{3}$$

The solution to Eq.(3) can be derived, i.e.,

$$\overline{u}(n) = -\sqrt{Ce^{an} - b} \tag{4}$$

Where $b = \dfrac{g\beta\Delta\theta\sin\alpha}{c_D}$, *C* is a constant that will be determined later by couplying with the above slope flow. ”-” indicates the flow is downslope.

$$\frac{d\overline{u}(n)}{dn} = -\frac{Cae^{an}}{2\sqrt{Ce^{an} - b}} \tag{5}$$

2.2 Katabatic flow model above canopy

Katabatic flow above the canopy is characterized by Prandtl model. Prandtl model is a one dimensional model with the velocity that is expected a function of *n* only. The governing equations are shown in Eq.(9)

$$\begin{cases} g\beta\Delta\theta\sin\alpha = k_m \dfrac{d^2u(n)}{dn^2} \\ \gamma u(n)\sin\alpha = k_h \dfrac{d^2\Delta\theta}{dn^2} \end{cases} \tag{6}$$

Hence,

$$g\beta\Delta\theta\sin\alpha + \frac{k_m k_h}{\gamma\sin\alpha}\frac{d^4\Delta\theta}{dn^4} = 0 \tag{7}$$

The general solution to Eq.(7) can be obtained

$$u(n) = Ke^{-n/l}[\Delta\theta_s\sin(n/l) - C'\cos(n/l)] \tag{8}$$

$$u(0) = -C'K$$

Where $l = (\frac{4k_m k_h}{N^2 \sin^2 \alpha})^{\frac{1}{4}}$ is a mixing length, $K = \frac{g\beta}{N}\sqrt{\frac{k_h}{k_m}}$, and $\Delta\theta_s$ is the near surface potential temperature increase from the initial background value.

3. CONNECTION AT THE TOP

In order to maintain the consistency of the velocity and shear stress profile between the within and above canopies, the following Eq. (9) should be satisfied.

$$\begin{cases} \overline{u}(0)_{in-canopy} = \overline{u}(0)_{above-canopy} & \text{(9-}a\text{)} \\ \Delta\theta\big|_{n=0,in-canopy} = \Delta\theta\big|_{n=0,above-canopy} = \Delta\theta_s & \text{(9-}b\text{)} \\ \left.\frac{d\overline{u}}{dn}\right|_{n=0,in-canopy} = \left.\frac{d\overline{u}}{dn}\right|_{n=0,above-canopy} & \text{(9-}c\text{)} \end{cases}$$

Hence, we can obtain the velocity profile for katabatic winds above and within the plant canopy as follows:

$$\begin{cases} \overline{u}(n) = -\sqrt{Ce^{an} - b} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots - h \le n \le 0 \\ \overline{u}(n) = Ke^{-n/l}[\theta_s' \sin(n/l) - C'\cos(n/l)] \cdots\cdots\cdots\cdots n \ge 0 \end{cases} \quad (10)$$

Where

$$C = b + \frac{2K^2\theta_s^2 - abl(al+2) - 2K\theta_s\sqrt{K^2\theta_s^2 - abl(al+2)}}{(al+2)^2}$$

$$C' = -\frac{\theta_s}{al+2} + \sqrt{\Delta}$$

$$\Delta = \frac{K^2\theta_s^2 - abl(al+2)}{K^2(al+2)^2}$$

4. CASE STUDY

We considered different cases shown in Table 1 by varying atmospheric stability and slope inclination while other parameters are kept constant.The effects of different atmospheric stratification conditions are shown in Fig.2. The higher ambient stratification can decrease the katabatic flow velocity above the canopy but little influence on the flow within the canopy. Also, the strong stratification can squeeze the cold-air-drainage depth. For the steeper slope, the maximum velocity both above and within the canopy increase, however, the height at which the maximum velocity is obtained above the canopy decreases with increasing steepness. When the slope is steeper, the velocity is higher both above and within the canopies.

Table 1. Input parameters for model calculation

Parameters	Units	Case1 (weak stability)	Case2 strong stability	Case3 higher inclination
thermal stability (γ)	K/m	0.002	0.004	0.002
temperature deficit on slope (θ)	K	3	3	3
temperature deficit on canopy top	K	3	3	3
thermal expansion ratio (β)	1/K	0.003413	0.003413	0.003413
Gravity acceleration (g)	m/s^2	9.81	9.81	9.81
Brunt-Vaisala frequency (N)	1/s	0.008183	0.01157	0.008183
C_D		0.25	0.25	0.25
Leaf area per unit volume (a)	1/m	0.1	0.1	0.1
LAI		10	10	10
K_h	m^2/s	2	2	2
K_m	m^2/s	2	2	2

slope angle (inclination) (α)	RAD	0.0872 (5°)	0.0872 (5°)	0.1744 (10°)
canopy height (h)	m	20	20	20

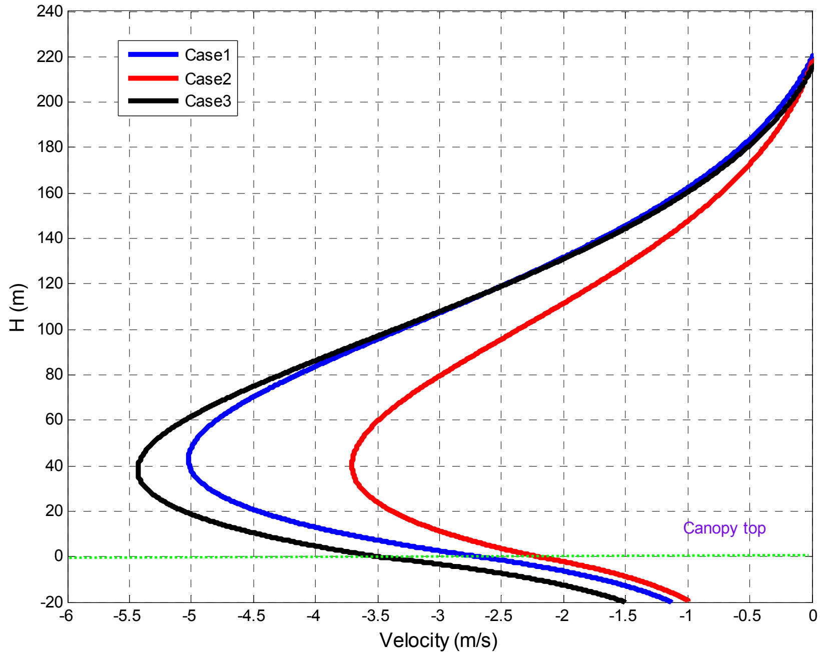

Figure 2. Predicted velocity profile for katabatic winds in different cases. The sign of '-' means the direction of velocity is downslope.

5. CONCLUSIONS

A new theoretical model coupling both above and within cold-air-drainage flows was developed. Prandtl's model was applied to the above canopy part, while the counterpart within the canopy was described by the modified canopy flow model by taking into account the buoyancy effect. Both the influence of the atmospheric stability and slope inclination are also examined.

References

Bergen, J. D. 1969. *Cold Air Drainage on a Forested Mountain Slope*. *Journal of Applied Meteorology*, 8(6), 884-895.

Devito, A. S., & Miller, D. R. 1983. *Some effects of corn and oak forest canopies on cold air drainage. Agricultural Meteorology*, 29, 39-55.

Finnigan, J. 2000. *Turbulence in Plant Canopies. Annual Review of Fluid Mechanics*, 32(1), 519-571.

Kitada, T., Okamura, K., & Tanaka, S. 1998. *Effects of Topography and Urbanization on Local Winds and Thermal Environment in the Nohbi Plain, Coastal Region of Central Japan: A Numerical Analysis by Mesoscale Meteorological Model with a k-epsilon Turbulence Model*. *Journal of Applied Meteorology*, 37(10), 1026-1046.

Komatsu, H., Yoshida, N., Takizawa, H., Kosaka, I., Tantasirin, C., & Suzuki, M. 2003. *Seasonal Trend in the Occurrence of Nocturnal Drainage Flow on a Forested Slope Under a Tropical Monsoon Climate*. *Boundary-Layer Meteorology*, 106(3), 573-592.

Ohashi, Y., & Kida, H. 2002. *Effects of mountains and urban areas on daytime local-circulations in the Osaka and Kyoto regions*. *Journal of the Meteorological Society of Japan*, 80(4), 539-560.

Pandtl, L. 1942. *Fuehrer durch die stromungslehre: Braunschweig,* Viewig und Sohn.

Raupach, M. R., & Thom, A. S. 1981. *Turbulence in and above Plant Canopies. Annual Review of Fluid Mechanics*, 13(1), 97-129.

Yi, C. 2008. *Momentum transfer within canopies*. *Journal of Applied Meteorology and Climatology*, 47(1), 262-275.

Yi, C., Monson, R. K., Zhai, Z., Anderson, D. E., Lamb, B., Allwine, G., et al. 2005. Modeling and measuring the nocturnal drainage flow in a high-elevation, subalpine forest with complex terrain. Journal of Geographical Research, 110, D22303, doi: 10.1029/2005JD006282.