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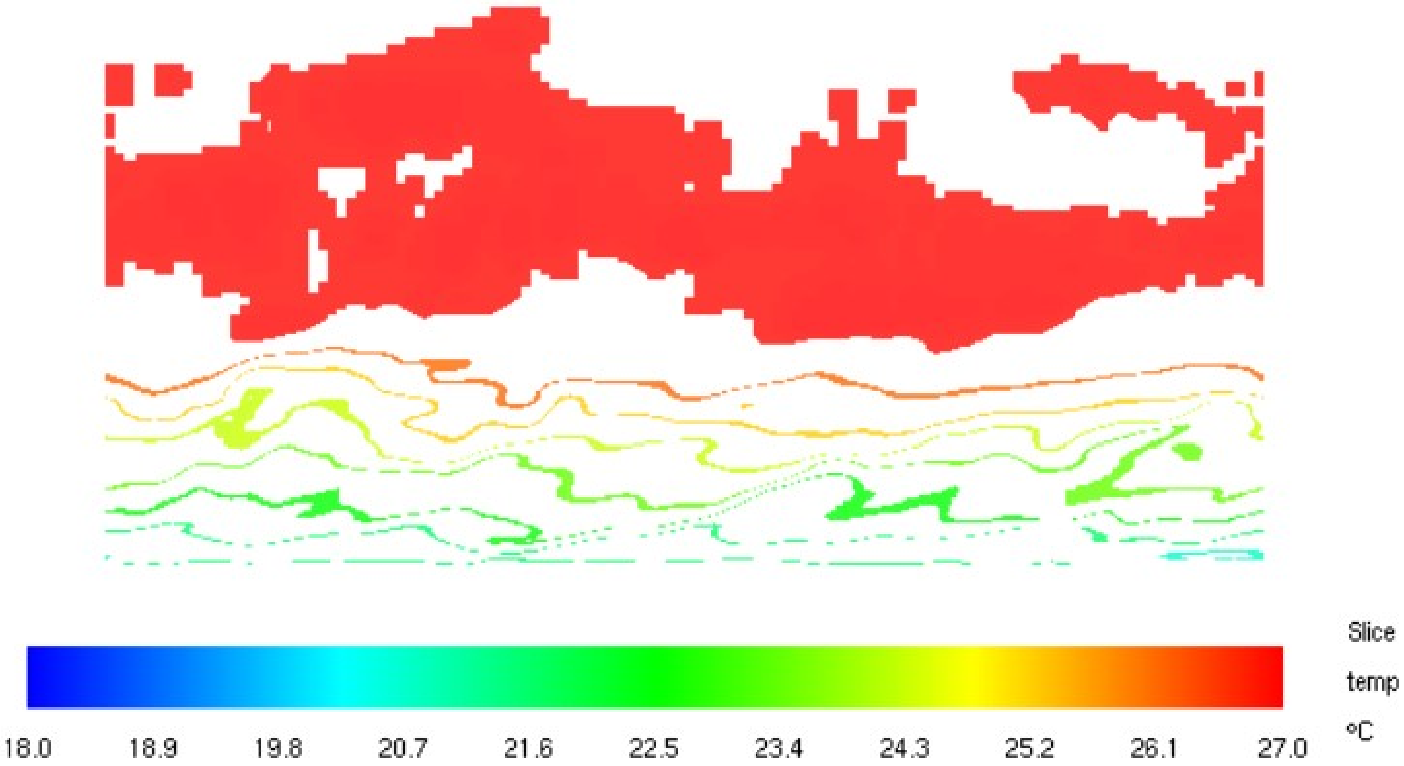
SIMULATION OF FLOWS THROUGH CANOPIES WITH VARYING ATMOSPHERIC STABILITY (PT. 2)

Nazmul Khan[1], Duncan Sutherland[2] and Khalid Moinuddin[1]
Victoria University[1] and UNSW[2]



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Cover: Thermal stratification is stable case, where ground becomes cooler comparing to atmosphere and ground becomes hotter comparing to atmosphere

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ABSTRACT

Large eddy simulation is performed of a flow through forest canopy over a range of atmospheric stabilities. A heat source is introduced at the top of the tree canopy to model the heating of canopy top by solar energy, Unlike our previous report [1] where an ideal Monin-Obukhov method was used for the surface heat flux variation, this study has introduced a varying volumetric heat flux in a sub-canopy region. The flow field develops naturally with the applied thermal stratification and pressure-driven flow. The forest canopy modelled using the leaf area density (LAD) of pine trees. The simulation is allowed for a sufficient time, of the order of 20000 s, to adjust with the applied heat flux in the domain. The simulation is attempted for two broad classes: stable and unstable situations with varying negative and positive fluxes, respectively. The simulation results are validated against the numerical study of Nebenfuhr et al. [2] and the field measurement taken at Ryningsnas, Sweden [3]; which shows a good agreement. The effect of canopy top heat flux on different atmospheric stabilities are studied in detail and we present mean velocity and Reynolds stresses. These results suggest that atmospheric stability may affect the rate of spread and pollution dispersion, especially in the case of unstable stratifications. There is a need to understand atmospheric stabilities for accurate analysis of wildland fire spread and fire intensity. Most importantly, flame characteristics must be carefully diagnosed with due account for different atmospheric conditions prevailing in real wildland fire for reducing property damage and loss of lives.

INTRODUCTION

The spread of wildland fire is dependent on various atmospheric stability conditions where the flow field is influenced by strong turbulent structure and exchange of momentum, heat and water vapor in an above forest canopies [2, 4, 5]. In near neutral conditions, turbulent wind flow over vegetation canopies exhibits universal characteristics (see for details at [6]). Within-canopy turbulence is dominated by ejection-sweeps cycle which are thought to be dual-hairpin eddy structures that develop due to Kelvin–Helmholtz instabilities induced by the inflected mean wind profile like those in plane mixing-layer flows [6, 7]. The turbulence structure of vegetation canopies is qualitatively different to that over a rough surface. The vegetation top of canopies is heated by solar radiation and the temperature is higher at canopy top than ground surface temperature [2]. Therefore, the flow through vegetation canopies fall in between boundary surface-layer and plane mixing-layer flows, which are highly complex in nature and difficult to capture in a simplified mathematical model. Additionally, the presence of a fire itself can modify both vegetation and wind fields which requires detailed information about the both vegetation and fire behaviour [8, 9].

Despite complexities in integration of atmospheric-vegetation flow structure, experimental field measurement [6, 10] and wind-tunnel observations [11, 12] have made progress to study the turbulent structure in and above canopies. Large eddy simulation (LES) is a technique applied by many authors [4, 13-17] for studying forest canopies a drag force dependent on LAD profile. Instead of using LAD profile of canopies which were introduced for the canopy drag force calculation, some recent studies attempted to introduce actual plants [18], arbitrary canopy heterogeneity [19] and terrestrial laser scanning data[20] for simulating canopy flow. However, simulation studies are typically restricted due to large computational costs [2].

In neutral or near neutral conditions, the flow through vegetation canopies are relatively well known, but flow through vegetation canopies in unstable or stable atmospheric conditions have not been well studied. Although some studies [4, 19, 21] have implemented unstable stratifications the micrometeorological variation across wide atmospheric ranges in the context of flow dynamics, temperature and humidity field at vegetation scales. Moreover, performing numerical experiments in unstable and stable conditions have proved more difficult than in neutral conditions [22]. Nebenfuhr et al. [2] performed LES simulation for horizontally homogeneous pine forest for different atmospheric stability conditions and compared to field measurements [3, 23] in the south-east of Sweden. In the simulation a potential temperature transport equation was solved with a heat source term that introduced thermal stratification according to measurement data of canopy top heat flux. The canopy to heat flux data were quantified based on the stability parameter, h/L, where h is the canopy height and L is Monin-Obukhov length. The purpose of this stability parameter is to compare with Monin-Obukhov similarity theory [24] for identifying unstable, unstable but near-neutral, neutral, stable but near-neutral, stable and very stable classes in the flow. In this study, we aim to develop a similar sub-model within FDS (Fire Dynamic Simulator) and validate against the numerical and experimental studies [2, 3]. If this is successful, then FDS can then be used for many applications of fire scenarios involving thermal stratifications.

METHODOLOGY

The model is set up with a rectangular domain of (*30h x 15h x 15h),* where *h* is the height of canopy (20m). An FDS coordinate system with x, *y* and z relate to the streamwise, lateral and vertical directions, respectively with a grid of *(60, 60, 150)* cells including a grid stretching in a vertical direction with a first point at z = *0.25m*.

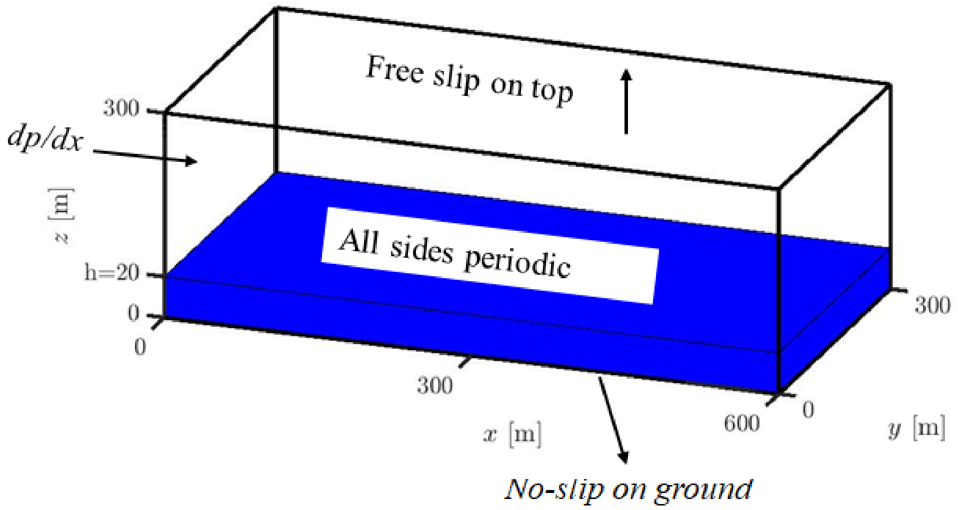


FIGURE 1 SIMULATION DOMAIN: BLUE IS THE HOMOGENOUS CANOPY AND BOUNDARY CONDITIONS ARE LABELLED AS SHOWN IN THE FIGURE. FORCE VECTOR, *F* (F = *DP/DX*) IS APPLIED IN X DIRECTION

Periodic boundary conditions are imposed in both x and y directions, while a free slip boundary condition is applied at the top of the domain. The ground is defined as a no slip boundary with a roughness coefficient of 0.02 following Nebenfuhr et al. The ambient temperature is 27°C in all simulations. LES simulation is performed with a constant Smagorinsky turbulence model without using any radiation sub-model. For the fully developed flow, the simulation is run as long as 20000s before taking ensemble averaged of mean velocities in all direction in space and time. The wind flow is developed by applying a constant pressure driven force. A horizontally homogenous pine forest tree is modelled as a region of aerodynamic drag over the bottom 20m of the domain xy plane by incorporating a canopy drag model within the FDS model.

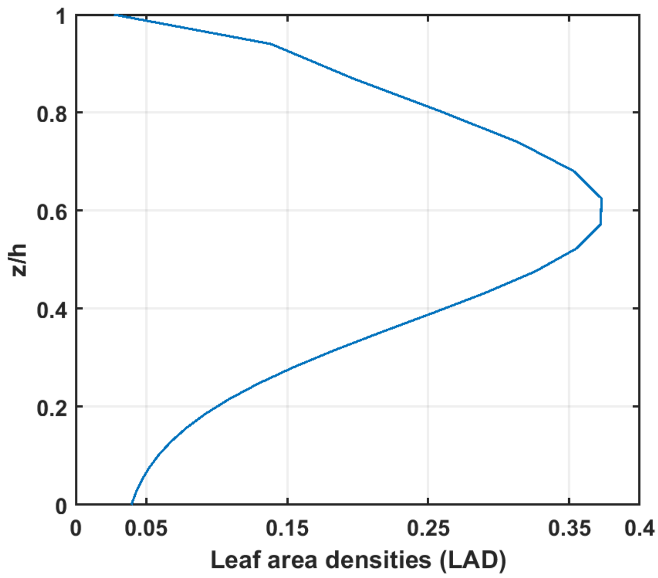


FIGURE 2 THE LAD PROFILE OF SCOTS PINE TREE, WHERE H IS THE CANOPY HEIGHT (20M)

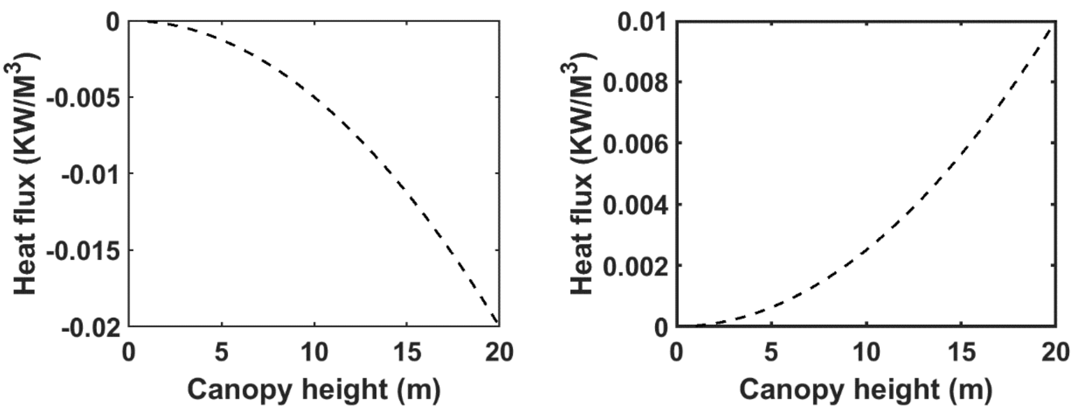
The drag coefficient is an input parameter with a value of 0.2 is used for this study. For the drag force exerted by tree canopy is modelled by LAD of Scots pine trees. The LAD profile shown in Figure 2 is from the Ryningsnas forest [3] . The drag model [25] is

$$F_{drag} = -cDa_f(z)u_i||u|| \qquad (1)$$

where *F_{drag}* is the draf force, *u_i* is the ith component of velocity, *a_f* is the LAD, *cD* is the drag coefficient and IIuII is the magnitude of wind velocity. This canopy drag model is developed and applied by Duncan et al. in both homogeneous and heterogeneous tree canopy model [25]. The profile has a cumulative leaf-area index (LAI), *A_c*, in the vertical direction (z)

$$A_c = \int_z^h a_f \, dz \qquad (2)$$

For the thermal stratification, Nebenfuhr et al. [2] applied a heat source term in the temperature transport equation. Because FDS uses a low-Mach number approximation it is more convenient to prescribe heat release rate over a volume which models heating of the canopy region by solar radiation. The volumetric flux applied for the stable and unstable cases are shown in Figure 3(a) and 3 (b), respectively. The volumetric heat source is chosen as varying in strength from canopy top to ground to match other studies [2, 4]. The heat fluxes are shown in Figure 3. This heat flux is applied uniformly across the canopy in the x- and y-directions.



(a) Volumetric flux in stable case (b) Volumetric flex in unstable case

FIGURE 3 THE VOLUMETRIC HEAT FLUX APPLIED IN (A) STABLE AND (b) UNSTABLE CASES VARYING FROM CANOPY TOP TO BOTTOM

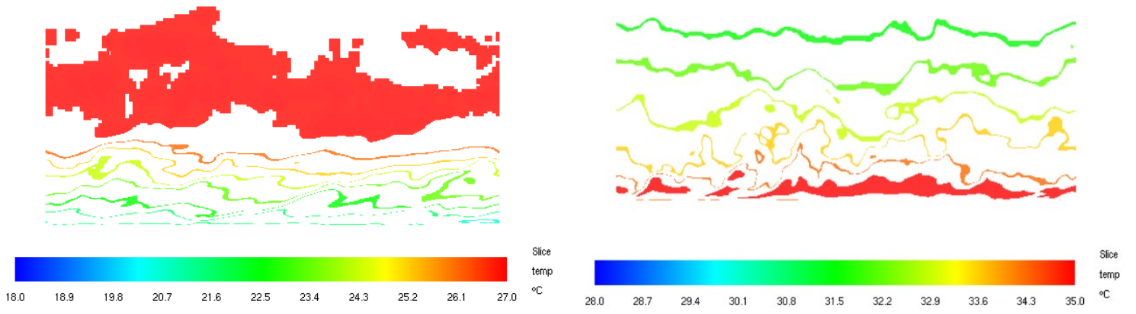
Cases	Max volumetric flux (KW/m³)	Force vector F(N)	Physical meaning
Stable	-0.02	4e-03	Ground temperature is lower than atmosphere where turbulence is suppressed
Unstable	0.01	3e-03	Ground temperature is higher than atmosphere where turbulence is promoted due to thermal stratification. Note that unstable situation is of our primary interest for fire development, fire intensity and the rate of spread, which may change significantly due to thermal stratification
Slightly unstable	0.01	5e-03	

TABLE 1 CASES WITH FLUX AND FORCE VECTOR VALUES

For the validation of Nebenfuhr et al. [2] study, we conducted one stable and two unstable cases as shown in Table 1. The maximum flux values and force vectors are shown in Table 1 with corresponding to physical meaning of stabilities.

RESULTS AND ANALYSIS

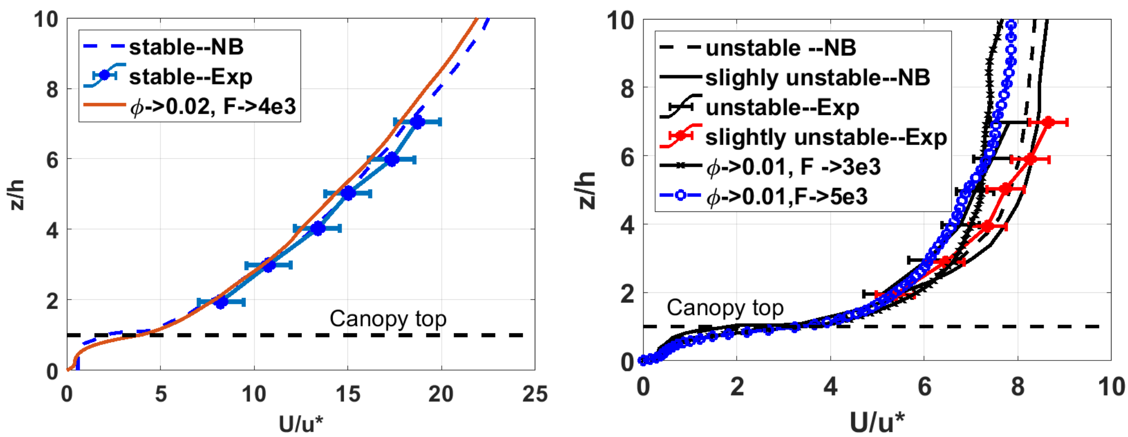
As we stated earlier, the thermal stratification is applied in the domain with the help of volumetric heat source in the sub-canopy region. In Figures 4 (a) and 4(b) the instantaneous contours of temperature for stable and unstable cases are shown, respectively. The differential temperature gradients exist in both situations, which are realistic with respect to physics meaning of stable and unstable situations.



(a) Stable stratification (b) Unstable stratification

FIGURE 4 THERMAL STRATIFICATION IS STABLE CASE, WHERE (A) GROUND BECOMES COOLER COMPARING TO ATMOSPHERE (B) AND GROUND BECOMES HOTTER COMPARING TO ATMOSPHERE

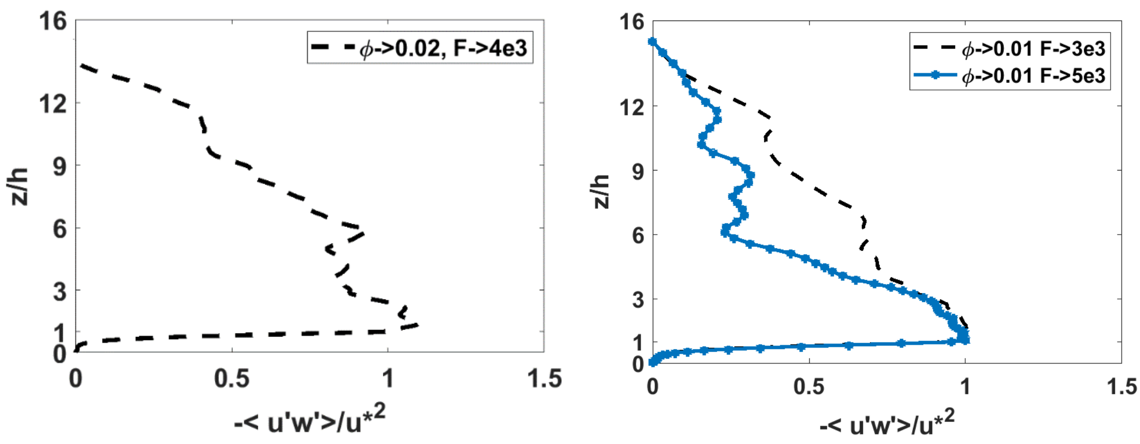
The streamwise horizontal mean (U) velocity is normalised by frictional velocity at canopy top following Nebenfuhr et. al. The non-dimensional mean velocity turning with height is shown in Figure 5 for different stability cases.



(a) Stable and very stable cases (b) Unstable and slightly stable cases

FIGURE 5 VALIDATION OF MEAN VELOCITY WITH THE NUMERICAL STUDY OF NEBENFUHR ET AL. [2] AND EXPERIMENTAL MEASUREMENT OF BERGSTRÖM ET AL . [3]. IN FIGURES, NB STANDS FOR NEBENFUHR ET AL. [2], EXP FOR EXPERIMENTAL MEASUREMENT OF BERGSTRÖM ET AL . [3], U FOR THE STREAM-WISE MEAN VELOCITY, Φ FOR VOLUMETRIC HEAT FLUX, F FOR APPLIED FORCE VECTOR IN X DIRECTION, AND U* FOR CANOPY TOP FRICTION VELOCITY.

First, the non-dimensional velocity profiles seem realistic in the context of development of wind profile with an inflection point in sub-canopy region and subsequent generation of profile according to different stability definitions and applied volumetric heat flux. For the stable case, the simulation results non-dimensional velocity is compared with the numerical studies of Nebenfuhr et. al. [2] and the experimental study of Bergström et al. [3]. The non-dimensional mean velocity is matches with both simulation and experimental studies [2, 3] for the stable case as shown in Figure 5(a). Note that the Nebenfuhr et al. study was also validated against the experimental measurement of Bergström et al. [3]. The non-dimensional mean velocities of unstable cases are also in reasonably good agreement with both numerical and experimental studies as shown in Figure 5(b).



(a) Reynolds stress in stable cases (b) Reynolds stress in unstable cases

FIGURE 6 THE PRODUCT OF FLUCTURATION VELOCITIES IN STABLE (A) AND UNSTABLE (B) CASES

The product of fluctuation velocities, u'w', is normalised by square of friction velocity at canopy top and shown in Figure 6(a) and 6(b), respectively for the stable and unstable cases. This demonstrates the trend of statistical development of flows in the domain, which are similar to previous studies of Sutherland et al. [25].

CONCLUSION

The flow through homogenous forest canopies with varying thermal stratification is simulated and validated against numerical and experimental studies. The simulation results show how the atmospheric conditions can affect the flow fields due to thermal stratifications, for example, changing wind flow, shear stress and changing temperature forest canopies. It is obvious that the day and night temperature can be vital in characterising flow though forest canopies. This study is very fundamental and there are opportunities to expand this study to fire spread scenarios. Inclusion of a heated canopy in fire simulations may reveal mechanisms behind the behaviour of real fires. Temperature gradients may exist at night, extreme weather conditions and prediction when this occurs may be relevant to understanding when fire behaviour will settle down. In future, this study may extend to many complex wildland fire scenarios including recirculation of flow in canopy covered hills and forest clearing, ember shower models and grass fire cases for wildland fire spread and fire intensity and analysis.

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