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A PRELIMINARY REPORT ON SIMULATION OF FLOWS THROUGH CANOPIES WITH VARYING ATMOSPHERIC STABILITY

Nazmul Khan[1,3], Duncan Sutherland[3], Jimmy Philip[2], Andrew Ooi[2,3] , Khalid Moinuddin[1,3]
Victoria University[1], University of Melbourne[2] &Bushfire and Natural Hazards[3]

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ABSTRACT

Nazmul Khan, Institute for Sustainable Industries and Livable Cities, *Victoria University, Melbourne, Victoria 3030, Australia.*
Duncan Sutherland, School of Science, University of New South Wales, Canberra, Australian Capital Territory, Australia
Jimmy Philip, Department of Mechanical Engineering, University of Melbourne, Parkville, VIC, Australia
Andrew Ooi, Department of Mechanical Engineering, University of Melbourne, Parkville, VIC, Australia
Khalid Moinuddin, Institute for Sustainable Industries and Livable Cities *Victoria University, Melbourne, Victoria 3030*, Australia,

Large eddy simulation is performed for a flow through forest canopy applying various atmospheric stability conditions. The canopy is modelled as a horizontally homogenous region of aerodynamic drag with a leaf-area density (LAD) profile approximating the profile of a Scots pine tree. Varying atmospheric stability is incorporated into the simulation by applying varying heat flux in two different ways; (i) a surface heat flux prescription using Monin-Obukhov similarity functions and, (ii) a canopy heat flux model where heat from the canopy is modelled as distributed volume heat source. When the surface heat flux was prescribed, five stability classes: very unstable, unstable, neutral, stable and very stable are modelled while for canopy heat flux model three classes: stable, unstable and neutral are simulated for this study. We observe, realistically, that the stable and very stable velocity profiles are leaned towards right to neutral velocity profile indicating wind dominated flow. On the other hand, unstable and very unstable velocity profiles become more vertical indicating buoyancy dominated flow. In all velocity profiles, an inflection point is observed in the dense canopy region. Expected variations in the temperature profiles are also observed – higher near-ground temperature for unstable and very unstable cases and converse is true for stable and very stable cases. Simulations involving exponential heat source variation vertically for forest canopy is ongoing for validation with experimental data and other similar studies. Once validation is obtained, parametric study with various atmospheric stability can be carried out in order to improve operational models.

Keywords: atmospheric surface layer, forest canopy, turbulence, thermal stratification, turbulent kinetic energy.

1. BACKGROUND

During the night, the ground is cooler than the atmosphere while the ground is hotter during the day. Due to this temperature difference, the mean wind speed profile observed in the atmospheric surface layer (ASL) takes different form than an ASL in neutral (no temperature difference) conditions.. An atmosphere can be considered stable, when the ground is cooler (in the later part of the night extending to the early morning) and an atmosphere can be considered unstable, when the ground is hotter resulting in lifting of the air (in the middle part of the day to dusk time). However, a temperature difference may occur any time between the atmosphere and ground depending on weather conditions. An idealised ASL is a boundary layer between a rough ground surface and atmosphere. However, having a closer look at the ground surface features (such as forest or urban canopy), we may find that ASL may take different forms. The presence of forest canopy would change turbulence structure and momentum exchange processes over a distributed canopy height range. The ASL will take a different form compared to an idealised ASL. Such forest-atmospheric interaction may affect the spread rate of the wildland fire [1-3]. Knowledge of this kind of forestatmospheric surface layers is of great interest in many applications, such as, climate change, greenhouse gases between forests and atmosphere, wind damage and wind throw at forest edges, the spreading of wild fires and dispersion of pollen and pollutants [1].

The fundamental theories of flux profiles and turbulent exchange processes in different atmospheric stabilities (without the presence of any forest canopy) were derived and improved by many authors [3-5] based on the universal similarity concept of Russian scientists, Monin and Obukhov [6]. According to Monin-Obukhov theory, the fluxes in the surface layer were parameterized by two dimensional functions; the universal functions for momentum and heat [3, 4] . The different stabilities were identified based on the dimensionless flux profiles of moment and heat with a third dimensionless parameter made by ratio of height over Monin-Obukhov length. These flux profiles and stability parameterization (without the presence of any forest canopy) were validated by experimental measurements[4, 5], which are now mature enough to compare with simulation results.

Comparing to experimental measurement and empirical models, a very few numerical simulation works [1, 2] were attempted to study atmospheric stabilities in a forest canopy. Simulation of flow through homogeneous or heterogeneous canopies were carried out by us [1, 7, 8] alongside other researchers [1, 7, 8] for integrating forest canopies explicitly in terms of leaf area density (LAD) as a canopy drag force exerted on the flow. In those studies, the effect of different LAD profiles in a horizontally homogenous or heterogeneous forest canopies are studied with varying degrees of success establishing different turbulent structure and mixing analogies in both dense and sparse canopy scenarios. Instead of using LAD profile of canopies, some recent studies attempted to introduce actual plants [9], arbitrary canopy heterogeneity [10] and terrestrial laser scanning data [11] for simulating canopy flow. However, these studies had to impose flow restrictions in the simulation due to huge computational costs [1].

In neutral or near neutral conditions, the flow through vegetation canopies are relatively more studied comparing to unstable or stable conditions. Although some studies [2, 10, 12] have implemented unstable stratifications[1], the micrometeorological variation across wide atmospheric ranges is not well understood at wind dynamics, temperature and humidity field at vegetation scales. Moreover, performing wind-tunnel and numerical experiments in unstable and stable conditions has been found more difficult than in neutral conditions [13]. More recently, Nebenfuhr et al. [1] performed LES simulation for horizontally homogeneous scots pine forest tree with different atmospheric stability conditions and the simulation results were validated against the field measurement [14, 15] conducted in south-east of Sweden. This experimental measurement of heat flux data were quantified based on the dimensionless ratio of height over Obukhov length to parameterise stabilities. In their simulation, a potential temperature transport equation was solved with a heat source term for introducing thermal stratification according to measurement data at canopy top heat flux. The strength of this heat source term is purportedly equal to thermal radiation heat received by canopy top due to solar radiation. The purpose of this stability parameter were to compare with MoninObukhov similarity theory [6] for identifying very unstable, unstable, neutral, stable, and very stable stability classes in the flow.

[1] Canopy is heated differentially as a function of canopy height

An idealised vertical wind profile of mean horizontal velocity profile (in the absence of a forest canopy) is assumed to be a logarithmic wind profile, though power law approximation is also used. However, turbulent exchange processes in ASL, where a temperature difference between air and ground exists, is much more complex due to transport of vertical momentum and sensible heat. The presence of vegetation canopies would further change turbulent mixing process due to drag force exerted on wind flow by forest canopy. Another complication with the forest canopy is only the top layer of forest canopy is heated by the solar radiation. From the top layer, a gradual temperature gradient is generated all the way to the surface. This is mentioned as thermal stratification above. In this study, we are conducting two sets large eddy simulation (LES) of sub-canopy and above canopy wind flow

(1) when there is a temperature gradient exists between the air and ground due to surface heat flux variations – Prescribing surface heat flux.

(2) when there is a temperature gradient between the canopy top and ground -- Canopy heat flux model.

It is to be noted that item (2) study is extremely complicated and the preliminary work has been done. The final work and validation are ongoing for next stages of simulation.

2. NUMERICAL METHODS

2.1 NUMERICAL IMPLEMENTAION

For this study, continuity and momentum transport equations are solved in LES context while small scales are modelled by constant Smagorinsky turbulence model. For the temperature field, ideal gas equation is solved and the conservative form of enthalpy equation is satisfied for eliminating temperature anomalies. The simulation is performed in FDS with an inclusion of canopy drag model in the source code. This canopy drag model was tested by a number of studies by Sutherland et al. and the full details can be found in [8]. For the first category simulation, atmospheric temperature is used as an input parameter and then surface heat flux is modelled by Monin-Obukhov similarity functions. A wind profile is generated with an introduction of suggested Obukhov length in FDS, which is derived from Monin-Obukhov similarity functions for momentum and heat. According to this similarity function mean velocity and mean temperature are varied with height (z) (without the presence of any forest canopy) as following equations:

$$u(z)=\frac{u_*}{k}\left[ln\left(\frac{z}{z_0}\right)-\psi_M\left(\frac{z}{L}\right)\right] \tag{1}$$

$$\theta(z)=\theta_0+\frac{\theta_*}{k}\left[ln\left(\frac{z}{z_0}\right)-\psi_H\left(\frac{z}{L}\right)\right] \tag{2}$$

where, z_0 is the aerodynamic roughness length (≈ 0.02), k is Von Karman’s constant (≈ 0.41), θ_0 is ground level potential temperature and Monin Obukhov length, L, is defined by

$$L=\frac{u_*^2\theta_0}{\theta_* g k} \tag{3}$$

In Eq (3), g is the acceleration of gravity, ☐is the scaling potential temperature defined as :

$p_0\,R/(/W_{air}C_p)$ (4) $\theta_*=T(\qquad)$

$$p$$

where p_0 is typically 1000 mbar and $R/(/W_{air}C_p) \approx 0.286$, and u_* is the friction velocity defined as:

$$u_* = \frac{k\,u_{ref}}{\ln\left(\frac{z_{ref}}{z_0}\right)} \tag{5}$$

where u_{ref} velocity is taken at height of z_{ref}. Additionally, the similarity functions, ψ_M and ψ_H are implemented according to proposed Dyer's model [3].

For the first category, the simulation of five classes of stabilities are prescribed as shown in Table 1. These cases are categorized in terms of Obukhov length which enforces ground heat flux in the simulations.

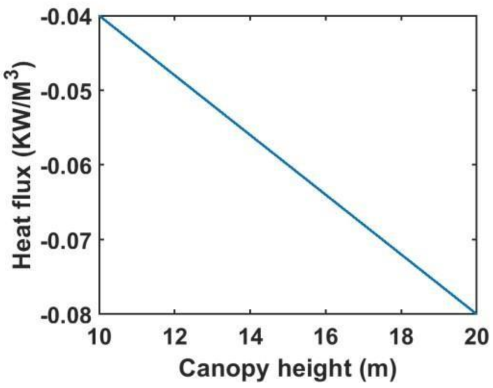
Table 1: Cases for surface heat flux models (category 1)

Stability type	***Obukhov length, L***	***Physical meaning***
stable	350	Surface is cooler than atmosphere
unstable	-350	Surface is hotter than atmosphere
neutral	1000000	Same temperature as surface and atmosphere
very stable	100	Surface is more cooler than stable case
very unstable	-100	Surface is more hotter than unstable case

For the second category, three cases are simulated as shown in Table 2 where we applied volumetric heat flux as an input data. The volumetric heat flux is varied from canopy top to downward as shown in Figure 1a and Figure 1b for the stable and unstable cases; respectively. We applied maximum heat flux at canopy top to a minimum at 10 m down in dense canopy region towards ground following the heat source model done by Nebenfuhr et al [1] and Shaw et al.[2]. Mean velocity and temperature profiles were not prescribed using Eqs (1-5). Rather, a pressure driven wind profile is generated applying a force vector in the streamwise direction for developing a wind profile with temperature stratification due to applied heat flux. The neutral case is set up with same pressure driven wind profile but without any input of heat flux.

Table 2: Canopy heat flux models (category 2)

Stability	***Flux condition***	***Physical meaning***
stable	Negative volumetric heat flux	Surface is cooler than atmosphere
unstable	Positive volumetric heat flux	Surface is hotter than atmosphere
neutral	No heat flux added	Same temperature as surface and atmosphere



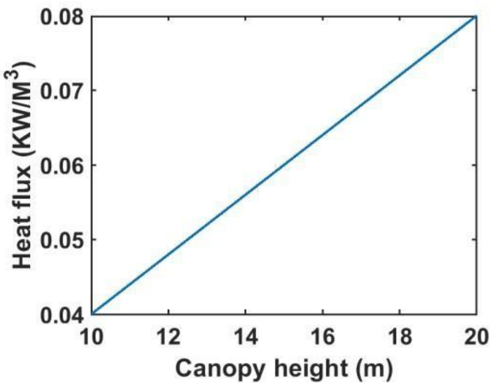


Figure 1a: Linear heat flux **1b: Linear heat flux**
For stable case (negative) from For unstable case (positive) canopy top to 10m
down from canopy top to 10m down

2.2 CANOPY MODELLING

For both sets of simulations (Tables 1 and 2), we modelled forest canopy profile as scopts pine tree, which is found in Ryningsnas forest of Sweden that has been used by Nebenfuhr et al. [1] for comparison of measurement data. The LAD profile is shown in **Figure 2**, which is prescribed within the physics-based model based on the method following Sutherland et al. [8]. The cumulative leaf area index is defined as following:

$$A_c = \int_z^h a_f \, dz \qquad (6)$$

where h is the canopy height and a_f is the leaf area indices with a mean value of 4.3.

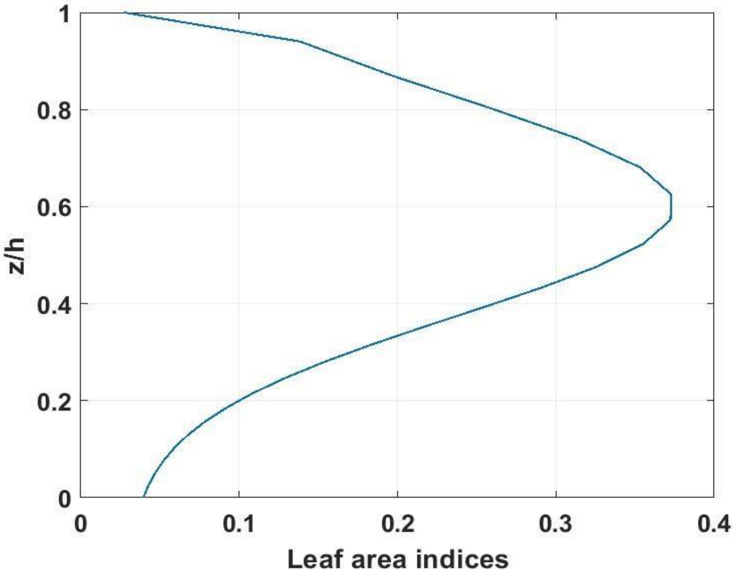


Figure 2: LAD profile of Scots pine tree

Leaf area indices with varying dimensionless height

2.3 MODEL SET UP

The model is set up with a rectangular domain of (*30h x 15h x 5h*) as shown in Figure 3. Meshing is done in an FDS coordinate system with *x*, *y* and *z* relate to the streamwise, lateral and vertical directions, respectively with a grid number of (*120, 60, 50*) cells. A grid stretching is applied in the vertical direction following FDS polynomial mesh leading to a resolution of approximately 0.25 m at bottom of the domain. Periodic boundary conditions are applied in both the streamwise and the lateral directions, while a symmetry boundary condition is applied at the top of the domain. A horizontally homogenous pine forest tree is integrated in *xy* plane with a vertical height of 20 m in the entire domain. Following literature values, the drag coefficient as an input parameter with a value of 0.2 is used for this simulation. The bottom of the domain is treated as a ground with an ambient temperature of 20^{0}C. For the fully development of flow, the simulation is run to16000 s time and ensemble average are taken in both time and space for data analysis.

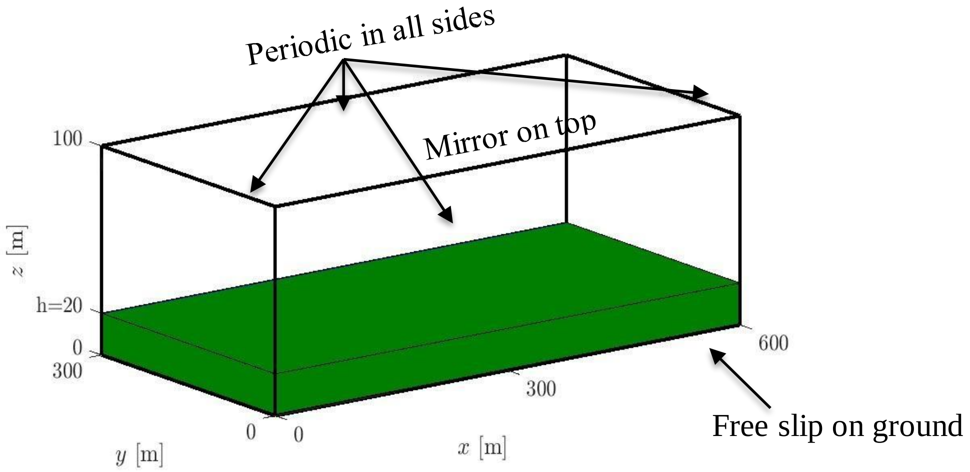


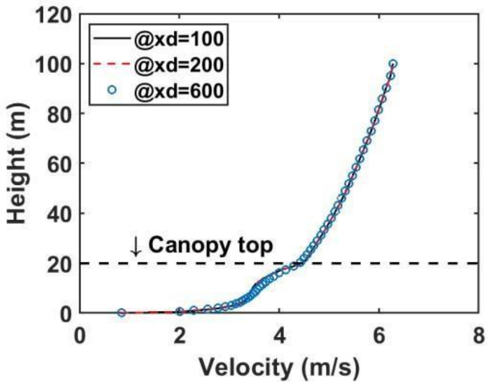
Figure 3: Simulation domain

In the figure, green color is the homogeneous canopy and boundary conditions are labelled by arrow sign.

3. RESULTS AND ANALYSIS

3.1 PRESCRIBING SURFACE HEAT FLUX

For the surface heat flux simulation cases, ground surface heat flux is varied according to applied conditions in the form of Monin-Obukhov length, which eventually solves the equations (1-2) for a mean velocity and temperature profiles defined for a specific stability class. For testing fully developed stable flow field, the spatial velocity profiles at different streamwise locations are shown in Figure 4a and Figure 4b for stable and unstable cases; respectively, which shows no changes in mean velocity at different locations.



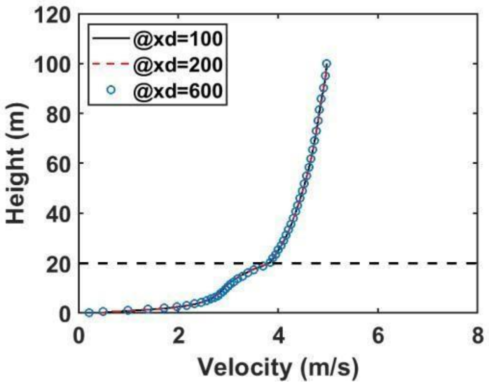


Figure 4a:Sstable case Velocity **Figure 4b: Unstable case** at different
xd (x distance) Velocity at different x locations for stable case. The
locations. dotted line stands for canopy top.

The stream-wise horizontal mean velocity variation with height is shown in Figure 5 for different stability cases for comparison purposes. First, the velocity profiles seem realistic in the context of development of wind profile with an inflection point in dense canopy region and subsequent generation of profile according to different stability definitions applied with the help of Monin-Obukhov length. It seems realistic that the stable and very stable profiles are showing shifted towards right to neutral velocity profile indicating wind dominated flow. Moreover, unstable and very unstable profiles become more vertical with a clear evidence of buoyant contribution of turbulent kinetic energy comparing to neutral, stable and very stable cases. Heated ground contributes to this buoyancy. It may be anticipated that with very stable scenario, a sub-canopy or above-canopy fire can spread quickly than other scenarios, as the wind can lean the flame more close to unburnt fuel ahead and heat them up more quickly via radiation and convection.

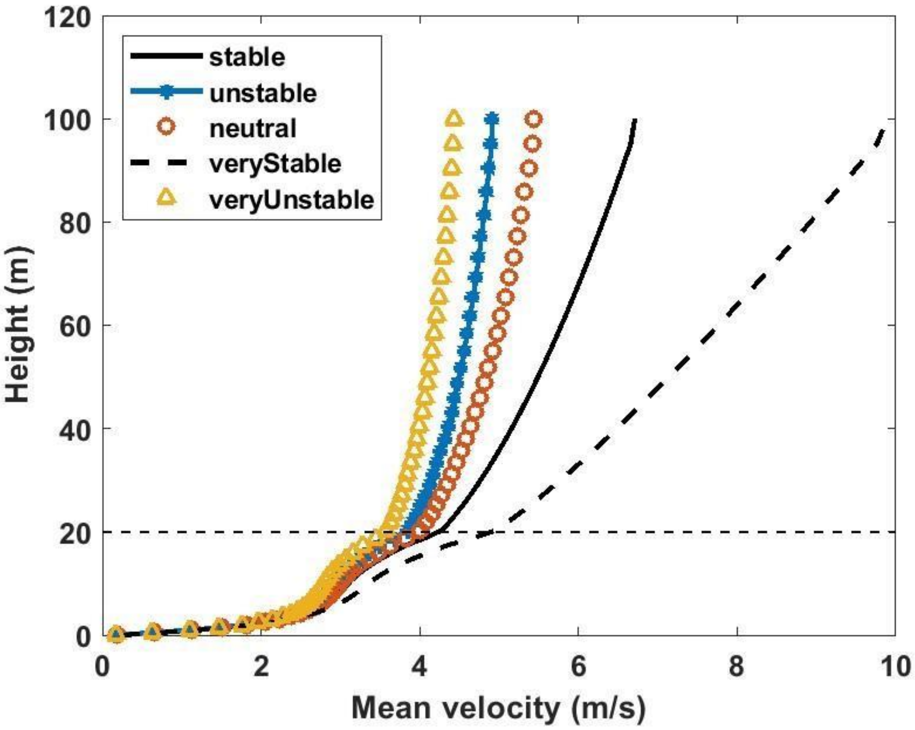


Figure 5: Velocity Profiles in surface heat flux model
Ensemble averaged mean velocity with varying Obukhov length

Mean temperature profiles are also shown in Figure 6 for all stability classes. The temperature profile of neutral case is showing no change in temperature as expected in neutral situation. For the very stable case, there is a significant increase of atmospheric temperature compared to ground as the thermal stratification (in air) causing temperature to rise in atmosphere. However, for unstable cases, there is a decrease of temperature in atmosphere and higher temperature on ground causing negative temperature gradient in unstable situation as expected. Overall, there is a decrease in temperature in all unstable cases while temperature has increased in all stable cases in atmosphere compared to ground that are expected.

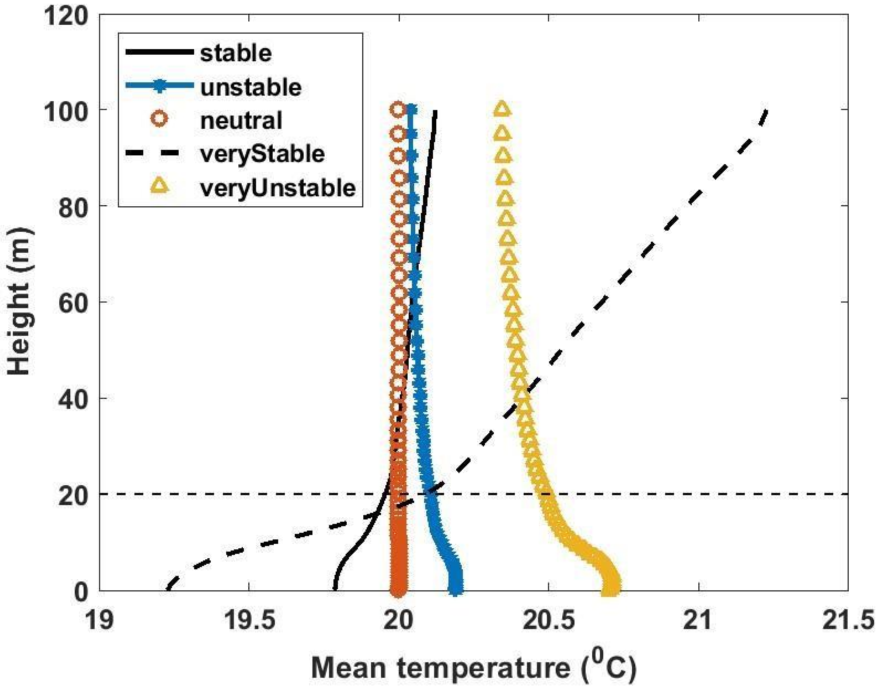


Figure 6: Temperature profiles in surface flux model
Ensemble averaged mean temperature with varying Obukhov length

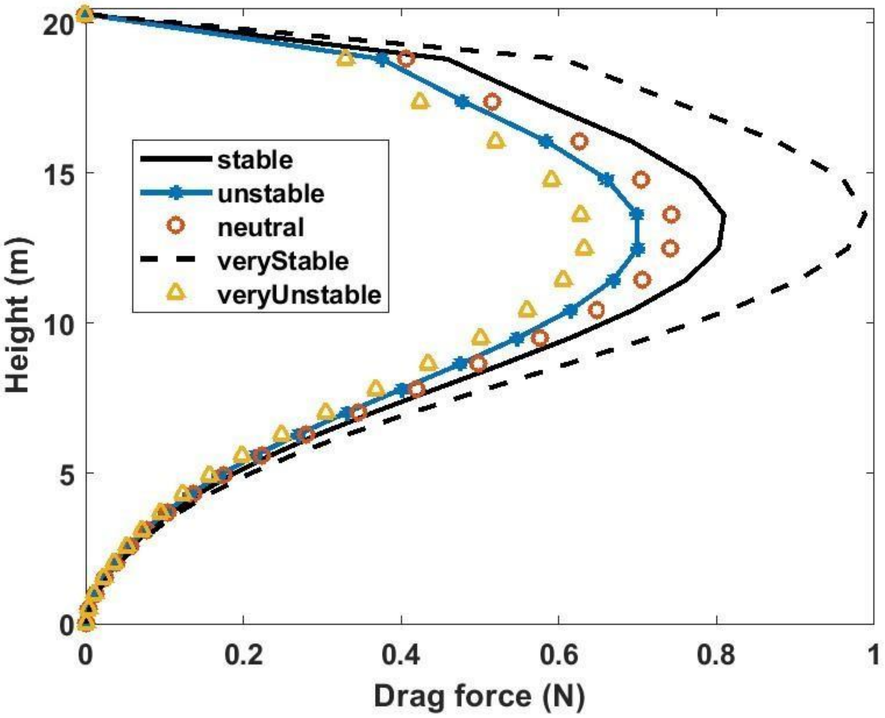


Figure 7: Drag force profiles
Drag forces with varying Obukhov length

The profiles of drag forces are also shown in Figure 7, which are following the velocity profiles in order for the all stability classes. The highest drag force is found corresponding to highest leaf area indices point as expected. Overall the profiles of drag forces are also similar to LAD profile as drag forces are proportional to leaf area density.

3.2 CANOPY HEAT FLUX MODEL

As we stated earlier, canopy flux is modelled by applying a heat flux starting from the canopy top to downward in a diminishing fashion following Nebenfuhr et al. [1] and Shaw et al. [2] The model is tested for preliminary simulation applying linearly diminishing flux profile as shown in Figure 8a and Figure 8b; respectively for the stable and unstable cases. The velocity profile at streamwise stations; at xd =100, 200 and 500 locations are shown in Figure 8a and Figure 8b. Comparing to the previous surface heat flux models, the velocity profiles in canopy flux models are not self-similar. This is especially within the sub-canopy for the stable case and above-canopy for the unstable case. Please note that we are not interested in spatial profiles rather we are interested in ensemble averaged mean profiles of the velocity and temperature, which is also pointed out by Nebenfuhr et al. [1].

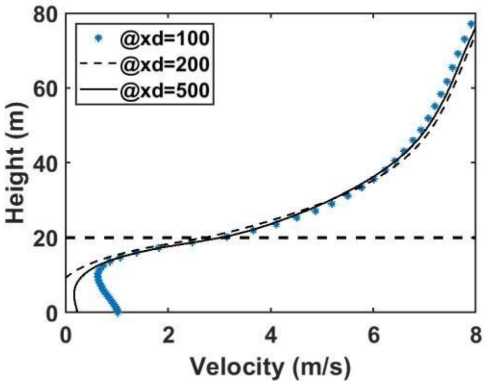
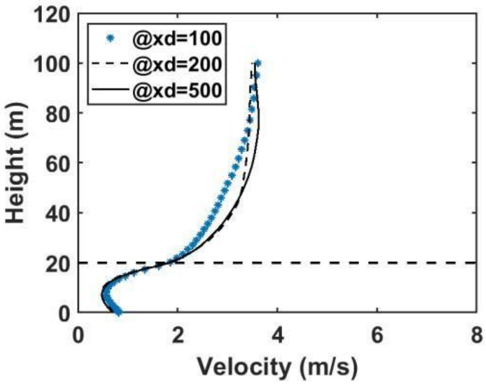


Figure 8a: Stable case
Velocity at different xd locations.



8b: Unstable case
Velocity at different xd locations

The mean horizontal velocity variation with height is shown in Figure 9 for the stable, unstable and neutral cases from canopy heat flux models. Comparing to our previous surface heat flux classes, the mean velocity profiles are showing similar trend in canopy heat flux models with due inflection point and subsequent development of wind profile. The stable and unstable classes are showing increasing and decreasing velocity compared to the neutral class; respectively following similar trend that we have seen in the surface heat flux models (category 1).

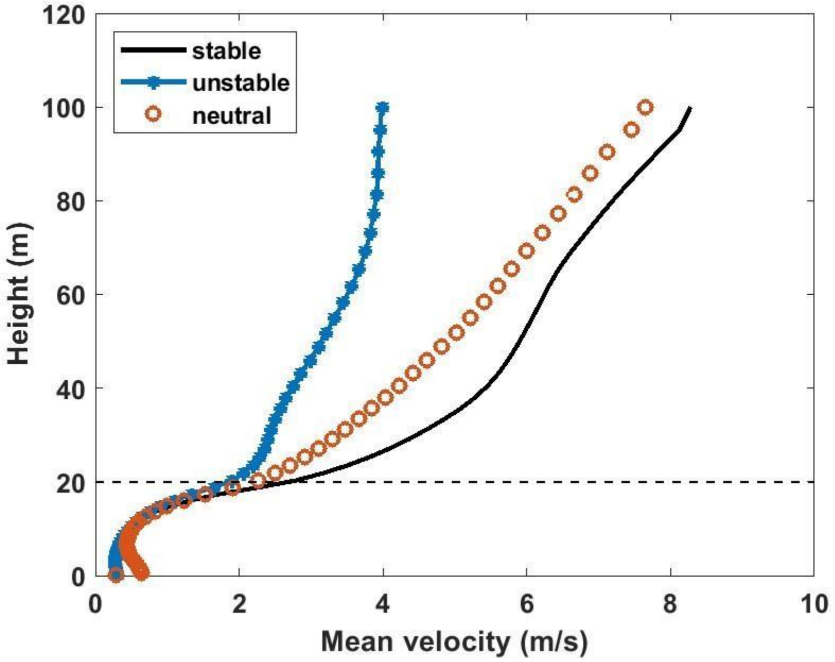


Figure 9 : Mean velocity of canopy heat flux model
Ensemble mean velocity of stable, unstable and neutral classes.

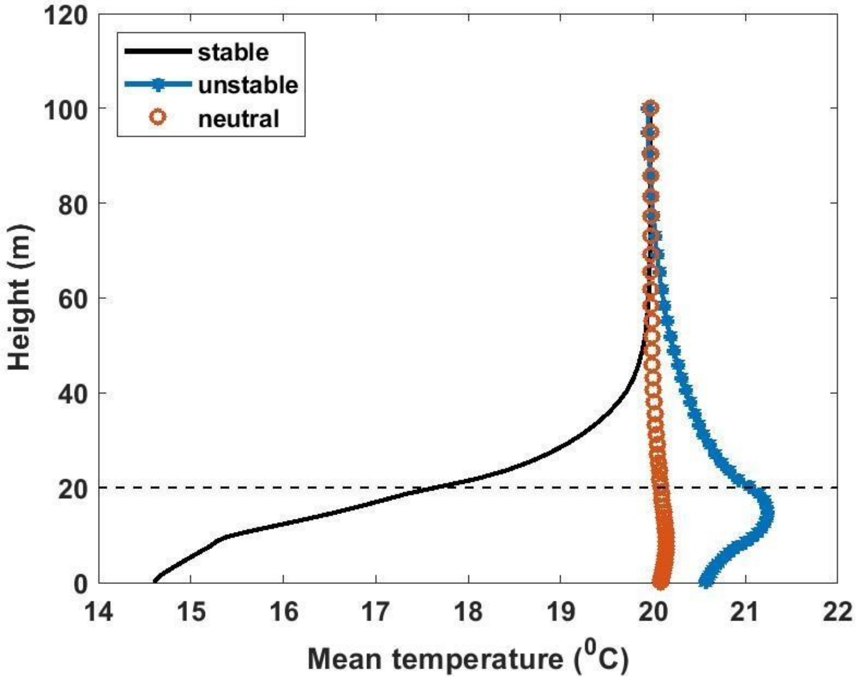


Figure 10: Mean temperature profile from canopy flux model
In the figure, mean temperature profiles of stable, unstable and neutral profiles are shown.

The mean temperature profiles of canopy heat flux models are shown in Figure 10, which shows similar trend as we have seen in the surface heat flux prescription. The increase and decrease of mean temperature in atmosphere at stable and unstable classes compared to neutral class; respectively clearly showing the trend as expected. However, for the neutral case, although there is a little bulge is observed in the dense canopy region but mean temperature remains unchanged as expected.

The vertical momentum flux in streamwise direction is shown in Figure 11 for the stable, unstable and neutral cases. The peak momentum flux is found at top of the canopy for all cases, where largest wind shear can be found. The momentum flux decreases linearly at height to zero, which are consistent with previous studies of Duncan et al. [8] . The profiles of momentum flux are also qualitatively similar to that of Nebenfuhr et al. [1] for similar studies.

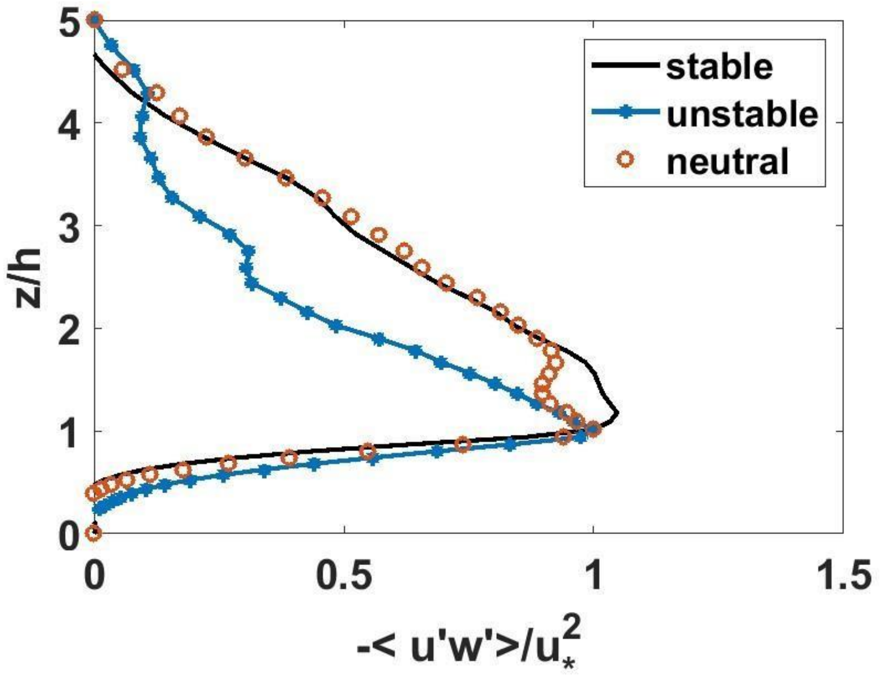


Figure 11: Ensemble averaged momentum flux
In the above figure, momentum flux is non-dimensionalised by square of friction velocity.

4. FUTURE WORKS

The preliminary simulation of flow through canopies with an idealised linear heat flux is tested successfully. The next set of simulations will use a more realistic/ experimentally measured exponentially decreasing heat flux profile from canopy top to bottom that depends upon the LAD. The exponential decreasing flux profile is shown in Figure 12a and Figure 12b for the stable and unstable classes; respectively.

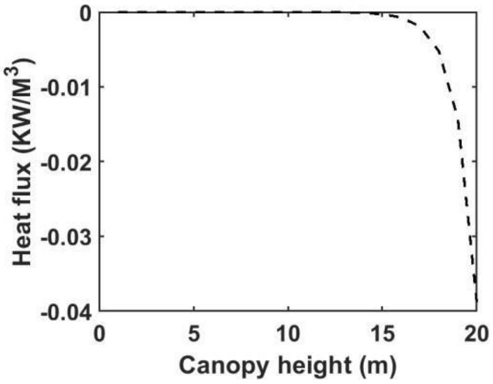


Figure 12a: Stable case
In the Figure, exponential flux profile.

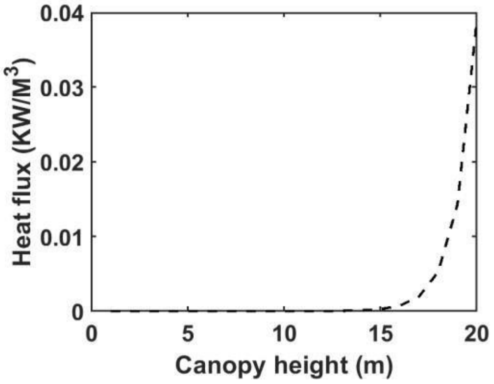


Figure 12b: Unstable case
In the Figure, exponential flux profile.

The next step of the project is to validate the simulation results against existing data in the literature. In Nebenfuhr et al. [1], a heat source is applied as a source term in a temperature transport equation with varying heat flux in the domain from canopy top to downward. Subsequently, Nebenfuhr compare their simulation results to experimental observations. FDS, however, uses the ideal gas equation to obtain temperature field and instead includes heating terms in the velocity divergence equation. Because of the different approaches, the simulation results from FDS need to be carefully compared to other simulations and experimental data to ensure they are correct. Once the validation is done successfully, this study can be extended for fire modelling cases in future.

5. CONCLUSION

Simulation of a flow through forest canopy with varying atmospheric stability is using the physics-based model FDS. The universal functions for momentum and heat are well understood in the absence of any forest canopy. In this study, we investigated the effect of the presence of a forest canopy. Two sets of simulations were conducted: the first set prescribed surface heat flux under a canopy using Moin-Obukhov similarity functions. The second set applied a volume heat source distributed over the canopy. The surface heat flux is prescribed based on ideal situations which are helpful to understand the effect of the atmospheric stability. The simulation results of mean velocity and temperature profiles are realistic and consistent with universal similarity theories. When a heat source with linearly varying heat flux is included in preliminary simulation, sensible result is obtained. The simulation of exponential heat source is ongoing for implementation and validation with experimental data and other similar studies. Overall, the simulation results show how the atmospheric stability can affect mean velocity, temperature and drag forces in a forest canopy. In future, this study can be extended for wildland fire cases which can contribute to knowledge in order to develop operational models to predict flow characteristics when atmospheric stability or instability is present.

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