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Defining the Turbulent Coefficients with The Effect of Atmospheric Stability in the Wake of a Wind Turbine

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Abstract:

Wind energy is one of cleanest form of renewable energy. Despite of wind industry is growing faster than ever, there are some roadblocks towards the improvement. One of the difficulties the industry facing is insufficient knowledge about wake within the wind farms. As we know, energy is generated in the lowest layer of the atmospheric boundary layer (ABL). This interaction between the wind turbine (WT) blades and wind introduces a low-speed wind region defined as wake. This wake region shows different characteristics under each stability condition of the ABL. So, it is necessary to know this wake region well, which is defined mainly by turbulence transport and wake shear. Defining the wake recovery length and width are very crucial for wind farms to optimize the generation and reduce the waste of power to the grid. So, to get the turbulent coefficients of velocity and length, we studied the large eddy simulation (LES) data for neutral ABL (NABL). According to [21] if we can present velocity defect and Reynolds stress in the form of local length and velocity scales, they become invariant. In our study velocity and length coefficients are 0.4867 and 0.4794 respectively, which is close to the theoretical value of 0.5 for NABL. Even though we have gotten some invariant profiles, because of the presence of thermal and wind shear power coefficients varied a little from the ideal condition.

Keywords—**Wind Turbine, Wake, Atmospheric Boundary Layer, Wake Length, Renewable Energy.**

I. INTRODUCTION

Wind turbines (WT) are very important in today's aspect. Sinceglobal warming is an issue, we would like to extract as much power which is renewable. WTs generate energy by being involved in the lowest part of the atmospheric boundary layers (ABL). Wake is a result when WTs produce power and leave behind wind at low speed.

It has been found that wind firm efficiency can be greatly affected by the stability of the atmospheric condition ([5]-[7]). And most of these Unsteady Reynolds-Averaged Navier-Stokes (URANS) solvers with the k-ε turbulence model has been used ([1]-[4]).

Heating, cooling, shear, rotation, turbulence levels etc. are related to the stability criteria for ABL. It has been well stablished that these factors are the main causes of restoring the wake deficiency of the WTs. However, the existing URANS methods can not consider the hidden wake turbulence phenomenon.

Actuator line method (ALM) has been transformed into a Large Eddy Simulation (LES) solver which has been processed in Open-source Field Operation and Manipulation (OpenFOAM) in search of modeling wind turbine with a realistic ABL ([7]- [14]). In [18]-[19] k-□ was used to simulate WT blades in high turbulence. Till now not many researchers worked with distinctive properties of flow in a wind park to observe these complex flows. From experimental studies wind-tunnel experiment on the wake flow behaviors below and above rotor disk height in a wind park in NABL conditions is significant [15].

Surface roughness can create serious impact wind farms concerning the presence of two external layers. Scaling velocity deficit and Reynolds stress with hub height velocity during the analysis can be concerning. Work done in [16] can be a great reference to achieve good performance in staggered wind farms. They proved that turbulent intensity and wake recovery can be influenced by farm layout. Also, hub velocity used for scaling here as well. Similarly, same approach was followed during wind tunnel investigation to show ABL turbulence affects wake of WTs [17].

In this paper when presented the wind turbine wake results, we proposed turbulent velocity and length scales to be scaling factors. To accomplish our experiment, we ran simulation using Simulator for Wind Farm Applications (SWOFA) which is categorized as LES solver [18]. After we stablished our turbulent scales, we presented velocity deficits, TKE and Reynolds stress scaled by these factors. Similar results were found when results are observed. Due to variation of temperature gradient inand wind shear CABL and NABL, scaling parameters were different too. We proposed different method of calculating velocity by the similar function.

II. TURBULENT SCALING

Turbulent flow changes its structure in direction of flow. Our calculation used theory from [21] while describing scaling factors. In our case we took xz plane averaged in the span direction, therefore the main component is in the x direction. So,

U= mean velocity, $\frac{\partial}{\partial x} \ll \frac{\partial}{\partial z}$ nearly everywhere

Fig. 1Vorticity Structure behind Wind Turbines

Equations we have used for the approximation of scaling are below:

Continuity equation

$$\frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} = 0 \qquad \text{(Eq 1.)}$$

Cross stream momentum equation

$$U\frac{\partial W}{\partial x} + W\frac{\partial W}{\partial z} + \frac{\partial \overline{u'w'}}{\partial x} + \frac{\partial \overline{w'^2}}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \nu\left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial z^2}\right) \qquad \text{(Eq 2.)}$$

Streamwise momentum equation-

$$U\frac{\partial U}{\partial x} + W\frac{\partial U}{\partial z} + \frac{\partial\left(\overline{u'^2} - \overline{w'^2}\right)}{\partial x} + \frac{\partial \overline{u'w'}}{\partial z} = \nu\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial z^2}\right) \qquad \text{(Eq 3.)}$$

The deficit scale can be written as-

$$\frac{(U_o - U)}{U_s} = f\left(\frac{y}{l}\right) \qquad \text{(Eq 4.)}$$

Where, obviously l can change in the downstream ($l = l(x)$). We know that turbulence intensity u is of orderU_s. So, we can expect that the Reynolds stress may be described by-

$$\overline{u'w'} = {U_s}^2 g\left(\frac{y}{l}\right) \qquad \text{(Eq 5.)}$$

Solution done in [21] for plane wake in neutral condition is as-

$$U_s = Ax^{-1/2}, \; l = Bx^{1/2}$$

III. METHODOLOGY

Previously for calculating velocity deficit researchers used to use either $(U_{abl} - U)/U_{hub}$ or $(U_{abl} - U)/U_{abl}$. Here, U_{hub} and U_{abl} do not change in the direction of stream or x axis. Since, the WT wake is turbulent, these parameters need to be varied as well in the steam direction. In our case we calculated flow as plane flow, where average flow is same in different plane for a given plane. We took the average of xz plane because there is a meandering effect along the span. Once we have calculated the average, we estimated the velocity defect of the respective plane. Contour plot for CABL and NABL are presented in Fig. 2 and Fig. 3. Location for the maximum defect in different x location was measured after maximum defect plane location was determined.

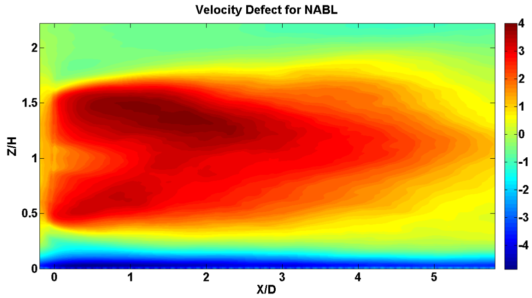

Fig. 2 Velocity defect (ms^{-1}) for NABL

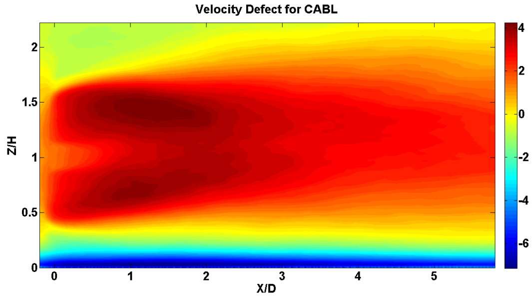

Fig. 3 Velocity defect (ms^{-1}) for CABL

Fig. 4 and Fig. 5 show the curves for velocity and length scales in NABL where regression was used. Calculated power coefficients are 0.486 and 0.479 for velocity and length respectively. This is very close to 0.5 which was proposed in [21]. We took NABL result as the validation since it's pretty close the theoretical value. Hence, we carried our experiment for CABL and the velocity and length coefficientsare 0.39 and 0.451 for CABL (Fig. 6 and Fig. 7).

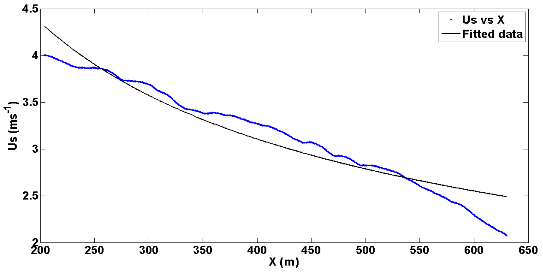

Fig.4Fitted curve to get a and b coefficients for $U_s = ax^{-b}$ (ms^{-1}) for NABL where a=57.34 and b= 0.4867

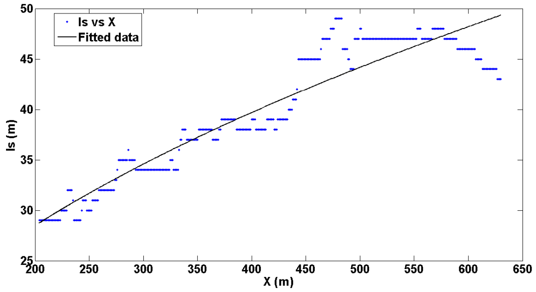

Fig. 5 Fitted curve to get a and b coefficients for $l_s = ax^{b}$ (m) for NABL where a= 2.245 and b= 0.4794

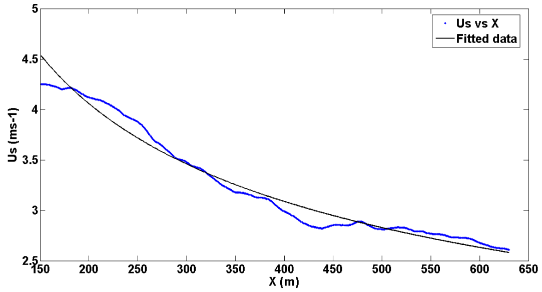

Fig. 6 Fitted curve to get a and b coefficients for $U_s = ax^{-b}$ (ms^{-1}) for CABL where a= 32.71 and b= 0.394

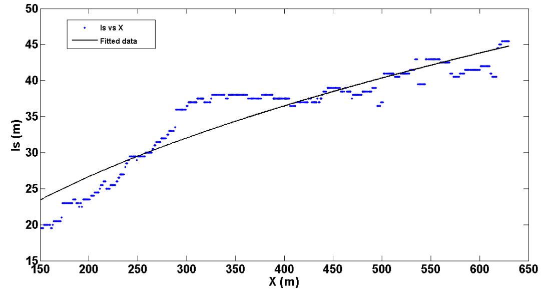

Fig.7Fitted curve toFitted curve to get a and b coefficients for $l_s = ax^{b}$ (m) for CABL where a= 2.436 and b= 0.4517

IV. RESULT

Reynolds stress, velocity deficit and TKE are the parameters are scaled using the velocity and length parameters. We started with presenting the velocity deficit which is the most important metric to measure the wake length. The most practiced formula for velocity deficit is either $(U_{abl} - U)/U_{hub}$ or $(U_{abl} - U)/U_{abl}$.

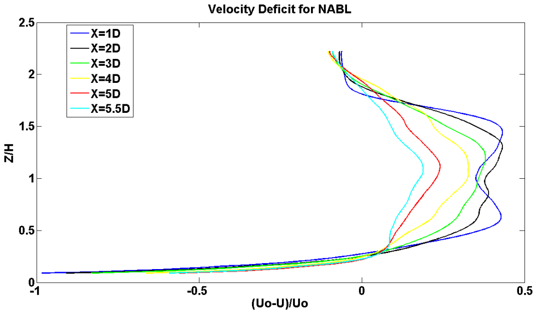

Fig.8Velocity deficit Scaled with U_{ABL} for NABL

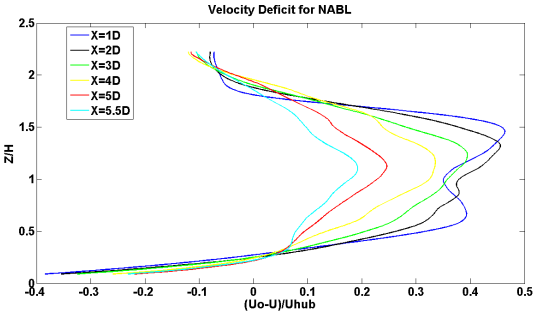

Fig.9Velocity deficit Scaled with U_{hub} for NABL

We derived deficit U_{abl} and U_{hub} along with the scale by using from turbulent analysis. Fig. 8 to Fig. 10 present the velocity deficit for 1D using various types of scaling. In Fig. 8 and Fig. 9 similar shape has not been seen. Due to not having a hub in our simulation w-shape is seen until x= 2D. Fig. 10 U_s has been used to present velocity deficit. Also, similarity shape comes after x= 2D at around 2.5D. Since U_s and $l_s$are both used here, and curves started to collapse starting from 2.5D. This becomes evident when local length and velocity parameters are used deficit becomes invariant.

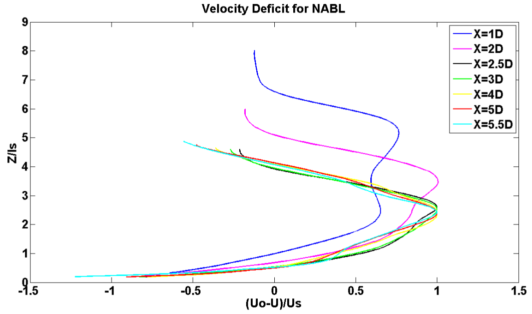

Fig.10Velocity deficit Scaled with U_s and l_s for NABL

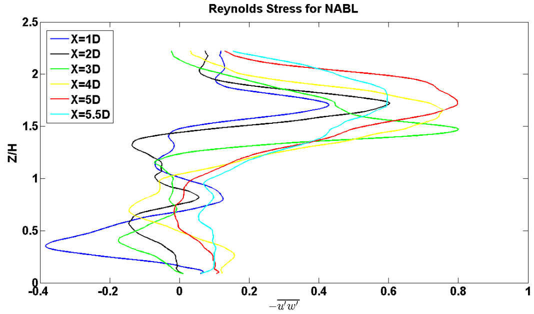

Fig.11Reynolds Stress without scaling for NABL

Fig. 11 to Fig. 13 presented turbulent coefficients scaled by Reynolds Stress. Reynolds stress is not scaled in usual cases. However, in this case results are scaled with U_{hub} and U_s. Fig. 11 and Fig. 12 are the presentation of Reynolds Stress without and with scaling with U_{hub}. Although the plots look similar, they are different in magnitude. However, while calculating $-\overline{u'w'}/U_s^2$ and plotting against z/l_s similarity become visible except for closer distance which is expected.

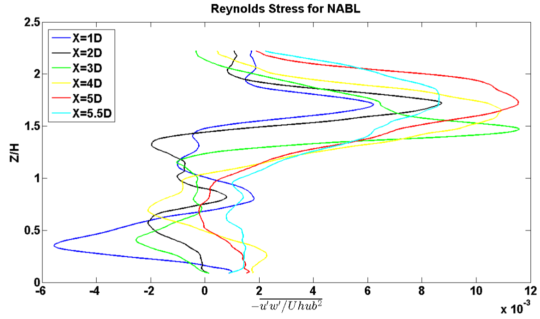

Fig.12Reynolds Stress Scaled with U_{hub} for NABL

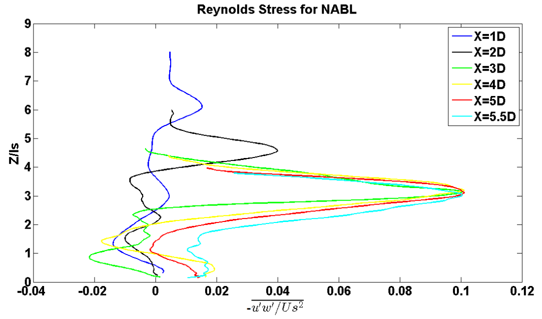

Fig.13Reynolds Stress Scaled with U_s and l_s for NABL

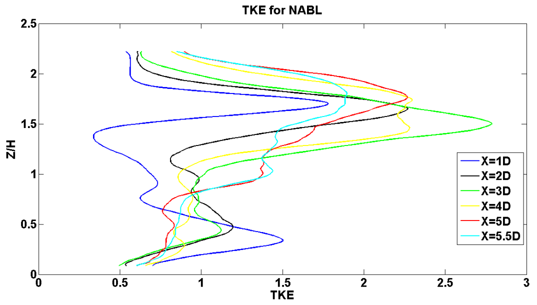

Fig.14TKE without scaling for NABL

We also generated same plots for TKE. U_{hub} was used for scaling where plots have similarity except the magnitude. Reynolds stress plots supposed to have similar magnitude level to the TKE plots, since $u'w'$ directly influences the TKE value. Moreover, they are varying in the x direction. When we incorporated U_s and l_s we got our desired similarity shape which matches the same pattern with Reynolds stress. Similarity shape becomes visible after = 2D as expected. Although we have seen some difference in the lower portion of the curves.

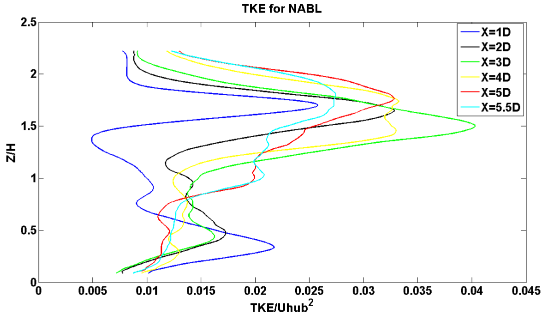

Fig.15TKE scaling with U_{hub} for NABL

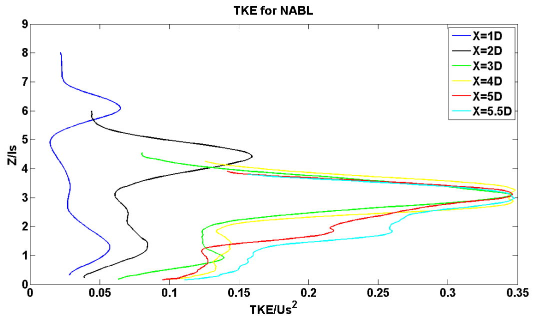

Fig.16TKE scaling with U_s and l_s for NABL

As we mentioned about scaling for NABL where coefficients were verified with the theoretical value. Now we will describe the scaling for CABL. We adopted the same methodas we followed for NABL to calculate the coefficients. We got values of 0.394 and 0.451 for CABL different than NABL which is expected in this case. It is due to heat flux accounted for CABL.

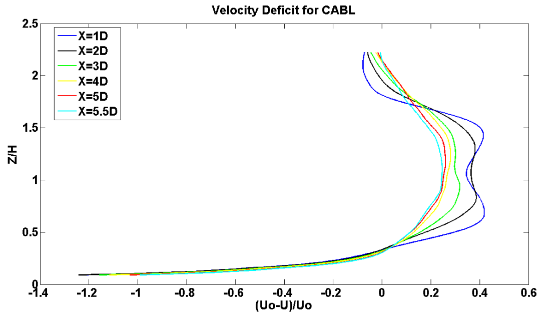

Fig. 17 Velocity deficit Scaled with U_{ABL} for CABL

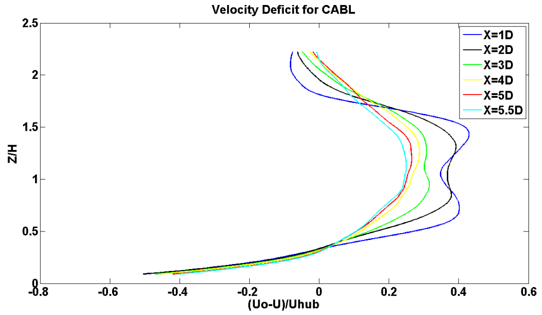

Fig. 18Velocity deficit Scaled with U_{hub} for CABL

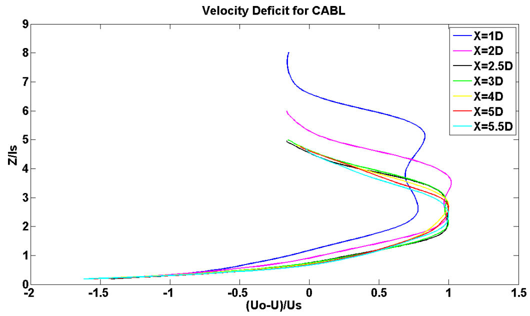

Fig. 19 Velocity deficit Scaled with U_s and l_s for CABL

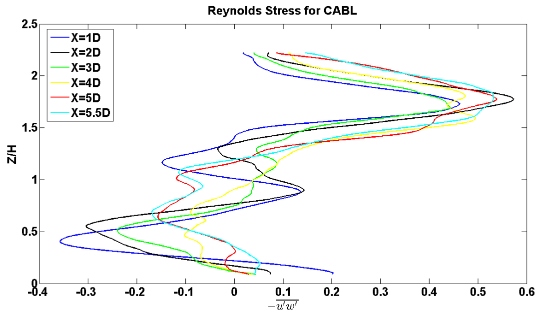

Fig. 20 Reynolds Stress without scaling for CABL

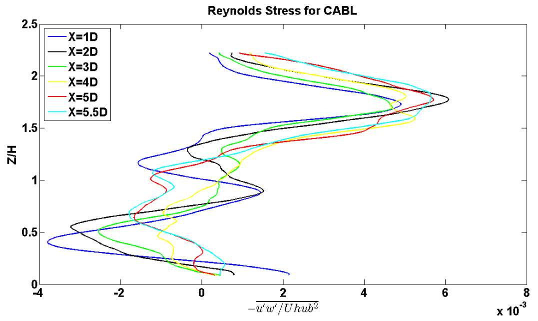

Fig. 21 Reynolds Stress Scaled with U_{hub} for CABL

In Fig.17 and Fig.18. deficit plots are expressed with U_{ABL} and U_{hub} for CABL. These plots are similar as we did for the NABL.The incident of decreasing deficit is starting from the beginning. This is not the expectation. On the contrarywhen scaled with the U_s and l_s, deficit plot starts collapsing in Fig.19 and invariance occurs after X= 2D. Similarity shape becomes prevalent at about X= 2.5D.Although turbulent scale is yielding larger wake length.

Results for CABL scaled with U_{hub} and $U_s$to present Reynolds Stress Fig. 20 and Fig. 21. Plots with no scaling provided similar result like NABL. Similarly, we were able to get the similarity shape except at the lower portion.

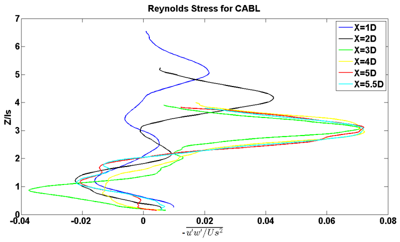

Fig. 22Reynolds Stress Scaled with U_s and l_s for CABL

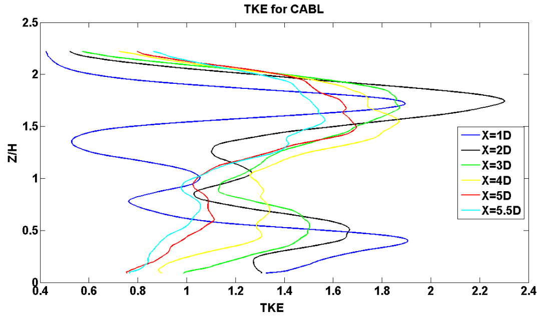

Fig. 23 TKE without scaling for CABL

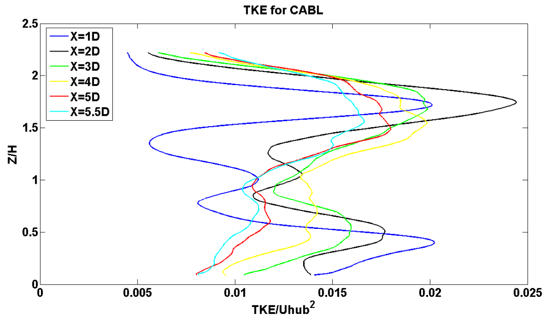

Fig. 24TKE scaling with U_{hub} for CABL

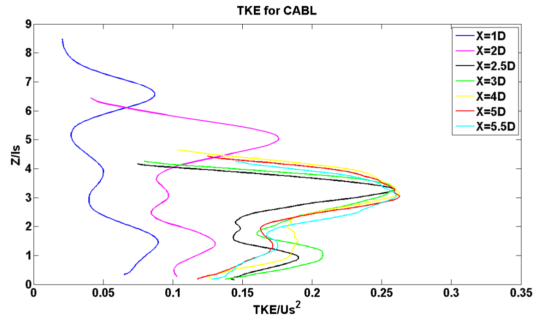

Fig.15 TKE scaling with U_s and l_s for CABL

V. CONCLUSIONS

In our simulation the coefficient values we achieved were different for NABL and CABL. It was normal since CABL had temperature gradient and temperature flux which opposite to NABL. NABL has zero gradient and zero flux. The results well matched with the theory for the plane wake. Also, we were able find the similarity profile. Response of experimental values would be interesting to compare with since theoretical derivation for CABL is not possible. Future work includes working and verifying with experimental data. Moreover, we did not cover for stable ABL. That could add more information to the study.

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Here I have used data from my master's thesis paper to write this paper.

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