POLLUTANT DISPERSION IN THE WAKE OF A HILL: A NUMERICAL ANALYSIS

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ABSTRACT

This paper aims at numerically determining a detailed pattern of the concentration profile due to the exhaust from plumes in the wake region of a hill-like obstruction. The pollutant concentrations at these points are locally very different from expected levels. For simulation and experimental ease, a squared sinusoidal equation is approximated as the hill profile. This may be replicated in a wind tunnel facility for experimental data acquisition. Popular turbulent models are used to simulate the problem in a finite element based solver. The effect of varying pollutant exhaust velocities, plume location and hill slope are investigated. We conclude that the farther away the plume from the hill, lesser is the pollutant trapped in the recirculation zone. Also, a steeper hill is found to give rise to a larger wake and corresponding extent of recirculation. Effect of pollutant density and the recirculation effects on pollutant dispersion in the leeward side of the hill are discussed at length. Such studies are of use in planning and locating exhausts for minimal interference with inhabited zones.

Key Words: Pollutant dispersion, Atmospheric boundary layer, Recirculation, Plume location, Numerical simulation, Flow over a hill

INTRODUCTION

Pollutant emissions from chimneys and vehicles are a major menace in industrialized regions. It will be a very useful exercise to map the flow of pollutants from a plume located at a designated point in a given landscape. Dispersion of pollutants when released at a point is quite uniform and very predictable when there is no obstruction is the field and the flow is uniform. These problems are locally aggravated when the flow stream is not uniform but disrupted in the presence of buildings or natural topological features like hills and plateaus¹,². An accurate pollutant flow data is very essential from the point-of-view of town planners and residential builders. Points of pollutant density above tolerable levels can be identified and the exhaust can be conveniently redesigned or altered to suit the environment. In severe cases, the human settlement itself can be avoided.
Atmospheric Boundary Layer (ABL) problems have gained significant interest in computational fluid dynamics with the advent of powerful computational skills and several finite volume, finite difference and large eddy simulation methods have been applied to this particular case. Subjects of computational interest are the turbulence model used and the methodology adopted to model the hill surface roughness (due to vegetation etc). Experimental techniques have been suggested for wind tunnel testing of models of sinusoidal hills with roughness incorporated in the form of surface irregularities that break the flow. Porous windbreak fences also have been used to imitate forestry.

**OBJECTIVE**

This paper aims at a systematic understanding of the two-dimensional variation of pollutant concentration as it disperses along with the air stream over a hill. Plumes located at various locations on both the windward and leeward sides of the hill are studied for pollutant flow patterns. Concentration variation is drawn for the whole profile. The focus, though, is on the disturbed re-circulating flow in the wake of the hill. This could serve as a step towards comprehending the complete pollutant dispersion pattern in a complex terrain, say, in an urban area where the disturbances could be of the form of a series of buildings or in a hilly terrain or mountain range.

**METHODOLOGY**

The two-dimensional domain is as shown in the Fig.1. The region under consideration is 3000 m long and 1000 m in height. The hill is approximated as a squared sinusoidal function, as is common practice in ABL problems concerning hills. For the purpose of multiple species flow analysis, the properties of carbon-dioxide are taken. Thus, here the two species would be that of clean air and that of carbon-dioxide which is considered as the pollutant. Mass fraction variation of the pollutant is obtained along the vertical at required intervals to a height of 100m, i.e. double the height of the hill.

![Fig. 1: The field under consideration with the generated grid](image)

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The wind inlet horizontal velocity follows a log law profile with

$$\frac{u}{u_0} = \frac{1}{\kappa} \ln\left(\frac{y}{y_0}\right)$$

where: $y =$ vertical height
$u =$ horizontal velocity at height $y$
$u_0, y_0$ and $\kappa$ are constants relating to surface roughness of hill.

The grid generated for numerical analysis is non-uniform boundary layer type mesh. Along the ground and hill surface though, the nodal density is increased for higher resolution; the smallest cell has dimensions of the order of 0.5m. The grid size increases as it moves away from the ground till it reaches a standard size of $50m \times 50m$ at the topmost edges. The total number of quadrangular nodal elements is over 10000 for every analysis. The control space dimensions and grid proportions can be seen in the Fig. 1.

The numerical model is solved using a finite element based FLOTRAN solver with the assumptions of irrotational and incompressible flow. Modeling of turbulence is important to capture flow field variations and the popular $k-e$ model is adapted here. This model has found prevalence over other turbulence models in ABL problems over the years and especially so in commercial CFD software like FLOTRAN. A reported minor drawback with the model with respect to the leeward stagnation point has led to the $S-\omega$ model but the former is applied in the current case for computational ease.

**RESULTS AND DISCUSSION**

Plume located in the windward side of the hill with varying exhaust velocity

A hill of aspect ratio $S=5$ (S being an index of the slope of the hill, numerically equal to the ratio of the base width $L$ of the hill to the height $H$) is chosen and the pollutant exhaust velocity is varied as 5, 10, 15, 20, 25 and 30m/s for this inspection.

The most observable variation from an undisturbed flow that can be seen for a pollutant discharge velocity of 10m/s are the two recirculation zones immediately before and after the hill, as depicted in Fig. 2. This reattachment point in the wake is also a function of the maximum ambient velocity as depicted in Fig. 3. The disturbance before the hill is due to and depends on the magnitude of the pollutant discharge velocity in the vertical direction. The wake behind the hill though, depends on the slope of the hill. The effect of varying slopes is discussed in the next case. For now, the highlight is on the variation of concentration (expressed as mass fraction of pollutant) for vertical pollution discharge velocities of 5, 10, 15, 20, 25 and 30m/s. Fig. 4 The first and most important observation is that higher velocities of release tend to push the pollutants out of the recirculation zone. Lower velocities of discharge make the pollutants less prone to move with the wind velocity upwards. It can be seen that in the upstream side, the lower velocities are liable to have a maxima within a height of 20m, a very probable height for human inhabitation.

The mass fraction then reduces upwards till one more increase in concentration can be seen. This can be correlated with the velocity vectors and the movement of pollutant particles in the vertical recirculation region can be pictured. On the slopes of the hill, the higher velocities yield a higher concentration, which is in agreement with the previous discussion as the altitude is higher now.
Fig. 2: Recirculation patterns on both sides of the hill

Fig. 3: Reattachment points for varying inlet velocity cases
Fig. 4: Variation of pollutant concentration with pollutant discharge velocity
**Variation in hill slope**

Here, the hill height $H$ is a constant while the base length $L$ varies according to the analysis requirement. For this case, the hill aspect ratio $S$ is varied and the results are inspected. We consider $S=5$ and $10$ for a constant pollutant release velocity of $10m/s$.

For the same pollutant discharge velocity and same height, we can notice in Fig. 5 that the pollutant concentration is high at lower altitudes for the higher values of $S$. For $S=5$, the concentration is high for a higher altitude though, which can be correlated with the pre-hill wake formation, especially due to the increasing slope of the hill.

The vertical recirculation, in fact, forces a lower concentration at lower altitudes, carrying the particles upwards and dispersing it over a larger vertical distance. Thereby, high-rise buildings in the pre-hill wake of a high slope hill; and low altitude structures in case of a low slope hill are susceptible to increased pollution levels.

![Graph showing variation of pollutant concentration with hill slope](image)

**Fig. 5**: Variation of pollutant concentration with hill slope

**Variation in density of pollutant**

For this analysis, we consider pollutants with variable densities; one denser than air and one rarer than air. For the purpose of demonstration, we take pollutants with the properties of carbon-dioxide and methane gas respectively. The hill with $S=5$ is chosen again and pollutant exhaust velocity $v = 10m/s$.

It is apparent Fig. 6 that the denser pollutant is taken to higher altitudes immediately after release due to the wake in the region,
notwithstanding the fact that it is heavier and lesser susceptible to move upwards. The rarer pollutant moves upwards gradually, and as can be seen clearly, makes it more prevalent at higher altitudes as it moves downstream. The denser pollutant, by then, has the tendency to move towards lower altitudes. So, considering human suburban habitation patterns, concentration of a rarer pollutant can be above accepted levels in the windward side and a denser pollutant in the leeward side of a steep hill.

![Figure 6: Dispersion for pollutants of varying density](image)

**Plumes on the leeward side of the hill**

Here, a hill of S=5 is considered and the plume is located at three points. The distance of this exhaust point is taken at 0, 100 and 200m from the base of the hill on the leeward side. The backward flow due to the vertical recirculation Fig. 2 is evident in the concentration patterns towards the farther locations of the exhaust. A careful examination of the Fig. 7 shows a shark decrease in concentration at a height of 10 to 20m for a horizontal distance of 50 to 100m against the direction of the wind. This corresponds to the aforementioned reverse flow. Outside this, the flow pattern is generally predictable with a uniform decrease in concentration as one moves away from the point of release upwards vertically as well as away from the exhaust point horizontally.

**CONCLUSION**

This study was aimed at comprehending the flow patterns in a vertical two-dimensional flow field carrying a pollutant over a hill. The results obtained have been discussed and may be summarized as below.

The exhaust speed of the pollutant is an important factor in deciding the gradient of the pollutant being dispersed in the horizontal as well as the vertical directions. As elucidated in case (A), higher the exhaust velocity, higher is the pollutant dispersion along the vertical; also, lower the velocity of release, higher is the concentration of pollutant in lower altitudes.

The maximum slope of the hill under consideration is another significant factor in the above analyses. For this purpose, the aspect ratio S was changed and studied. Case (B) inspects in depth the same and the findings are that a higher value of S induces a more prevalent wake in the windward side, thereby distributing the pollutant over a larger vertical distance. On the leeward side though, this effect is not so rampant and the hill with a lower aspect ratio exhibits higher levels of pollutant.
Fig. 7: Cases with plume location on the leeward side at 0, 100 and 200 m beyond the hill
The density of the pollutant being dispersed, as in case (C), is another factor in determining the concentration patterns. It is evident from the related charts that the denser pollutant is more susceptible to follow the velocity patterns and is thus affected more by the disturbances. Nevertheless, on the leeward side, this effect is not so extensive and the lighter pollutant tries to move upwards while the heavier one tends to settle downwards. The location of the plume on the leeward side causes a very disturbed pattern in the pollutant concentration; refer case (D). The variation, though, corresponds well with the velocity pattern in this region. The recirculation is the major cause of this back-flow and irregular distribution patterns. The immediate effect is the sudden decrease and the immediate increase of pollutant concentration along a vertical profile. These results are evident in the corresponding plots. The flow patterns, dispersion model and the concentration distribution are bound to change with other huge obstructions like large buildings in the way creating further more disturbances and recirculation regions. This basic study, although, will be a very important tool when deciding on placing small buildings, low-rise residential colonies, thin towers etc and can be handy in deciding spots of acceptable pollution levels.

REFERENCES
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To sit in the shade,
We have to plant a tree first