# The Effect of a Meteorological Tower on its Top-Mounted Anemometer ⋆

Dimitri Perrin [a,b] Niall McMahon [a,b,*] Martin Crane [a,b]
Heather J. Ruskin [a,b] Lawrence Crane [b] Brian Hurley [c]

[a] *School of Computing, Dublin City University, Dublin 9, Ireland*

[b] *Institute for Numerical Computation and Analysis (INCA), Royal College of Surgeons in Ireland Research Institute, York House, York Street , Dublin 2, Ireland*

[c] *Airtricity, Sandyford, Dublin 18, Ireland*

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**Abstract**

The wind-speed at a site can be measured by installing anemometers on top of meteorological (*met*) towers. In addition to other sources of error, accelerated airflow, or *speed-up*, around the top of met towers can cause incorrect anemometer measurements. We consider a particular example where an anemometer was located only 2 tower diameters above the met tower. Using a standard computational fluid dynamics package, we found the maximum error for this configuration to be 2% of the wind-speed. We conclude that a top-mounted anemometer should be located at the windward side of its met tower, raised 5 diameters above the top. This will reduce speed-up error to less than 1%.

*Key words:* meteorological tower, flow distortion, anemometer, measurement error

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* Corresponding author. Tel: +353 1 700 8449; fax: +353 1 700 5442.
*Email address:* nmcmahon@computing.dcu.ie (Niall McMahon ).

## 1 Introduction

Worldwide, wind energy is currently experiencing unprecedented growth, with total installed generating capacity growing from 14 gigawatts (GW) in 1999 to 48 GW in 2004 [1]. Since the energy density and power output of a wind turbine depend strongly on the cube of the wind-speed at hub height [2], and since the accepted overall uncertainty in the determination of the energy density and power output is between 4 and 6% for a turbine sited on level ground [3], accurate wind measurements are vital when assessing the economic viability of a proposed wind project.

The wind-speed at a site is measured by installing an anemometer on top of a meteorological (*met*) mast. The anemometer is ideally located at the same height as the hub height of the turbines proposed for the site [4]. The met mast studied in the present case was a 50 m high thin-walled tubular tower with an outside diameter of 0.15 m and an anemometer located 0.30 m higher than the top (Fig. 3). The tower was hollow, with a gap between its base and the ground (Fig. 1).

The flow pattern around a tower is two-dimensional for most of its height, becoming three-dimensional close to the top, where the air is accelerated over the free end [5]. This accelerated airflow is often called *speed-up*. In our study, the anemometer was located only two diameters above the top of the tower, close enough that wind-speed measurements were likely to be affected by speed-up.

In assessing the effect of the tower on the anemometer, we studied various configurations of wind-speed, turbulence and the slope of the local terrain. We also took into account the fact that the tower was hollow. This model was built using the commercial computational fluid dynamics (CFD) code Fluent [6], coupled with a simple analytical analysis.

## 2 Theory and Method

### *2.1 Modelling a Solid Tower*

#### *2.1.1 Considerations and Assumptions for a Solid Tower*

In a previous study, it was shown that the flow around a finite cylinder at a height of one diameter below the free-end is approximately two-dimensional; the speed-up is not influenced by the airflow far below the top of the tower [5]. For this reason, even though our tower had a height to diameter ratio of more than 300 ($H/D > 300$), it was necessary only to model the topmost 1.5 m, or a cylinder of height to diameter ratio 10 ($H/D = 10$).

### *2.1.2 Meshing and Boundary Conditions for a Solid Tower*

The Fluent model consisted of a quarter-sphere with a diameter 40 times that of the cylinder. The cylinder represented the topmost ten diameters ($H/D = 10$) of our met tower ($H/D > 300$). By considering the axial symmetry of flow around cylinders, it was only necessary to model half the tower: this permitted use of a dense mesh without leading to excessive computation time. The mesh for our model contains approximately 650,000 tetrahedral cells, most of them close to the tower. The half-cylinder was placed centrally.

In the case of a solid tower, there are five boundary conditions. At the bottom of the domain, the flow is two-dimensional. The use of a *symmetry* condition on the bottom face enforced this constraint. The flow symmetry about the centre line of the cylinder allowed us to use another symmetry condition on the single vertical surface. The tower itself was assigned a *wall* condition, implying zero wind-speed at the surface. The upstream curved surface was defined as a *velocity inlet*. This allowed us to specify the free-stream wind-speed and a turbulence intensity. We defined the downstream face as a *pressure outlet* with atmospheric pressure. The resulting model is shown in Fig. 2.

### *2.1.3 Calculating the Speed-up for a Solid Tower*

On completion of a simulation run[1], we recorded wind-speed values at specified positions close to the free-end of the tower. These were located at 30° intervals, on a circle congruent and concentric with the circumference and at a height of two diameters above the top of the tower (Fig. 3). These correspond to positions at which the centre of the anemometer may be located. An actual anemometer consists of three cups rotating on a fixed circular path around the centre of the device and so the wind-speed is not measured exactly at the centre of the device but rather on the path followed by the cups. From our simulations, however, we concluded that the difference between the speed-up estimated at the centre of the anemometer and the speed-up estimated on the circle followed by the cups is always less than 0.08% of the free-stream wind-speed. The wind-speed estimated at the centre of the anemometer, therefore, represents an acceptable approximation to the values recorded by an actual cup-device for the purposes of this study.

[1] One run comprises approximately 2,000 0.1 s time steps, with 50 iterative computing steps in each of them.

### 2.2 Modelling a Hollow Tower

#### 2.2.1 Additional Considerations and Assumptions for a Hollow Tower

The accelerating airflow around the top of the tower is at a lower pressure than the still air at the bottom of the tower, next to the ground, where the pressure is atmospheric. This sets up a pressure drop from the bottom to the top and gives rise to an airflow up through the hollow centre of the tower. We can compute the velocity of this internal airflow using the empirical Darcy-Weisbach equation [7], writing

$$\omega = \sqrt{\frac{2D\Delta p}{\lambda H \rho}} \tag{1}$$

where $\omega$ is the speed of the airflow exiting through the top of the tower, $\Delta p$ is the pressure drop from the bottom of the tower to the top, $D$ is the diameter of the tower, $H$ its height, $\lambda$ the pipe friction coefficient, calculated iteratively using the Colebrook-White equation [7], and $\rho$ is the air density.

#### 2.2.2 Calculating the Speed-up for a Hollow Tower

The internal airflow through the hollow tower can be captured by changing the top surface of the tower from a wall boundary to a velocity inlet. The air velocity assigned to this inlet is computed using an iterative process (Fig. 4). Essentially: (1) an initial run of the solid tower simulation provides a pressure value at the top of the tower; (2) using this value to calculate $\Delta p$ in Eqn. 1, we then estimate the internal airflow speed $\omega$ at the top of the tower; (3) we use this value for $\omega$ as the top boundary condition for the next simulation run in order to get a new estimate for the pressure drop; (4) this process is repeated until $\omega$ converges on a fixed value.

### 2.3 Modelling a Tower on Sloped Terrain

#### 2.3.1 Additional Considerations and Assumptions for a Tower on Sloped Terrain

We assumed that in the vicinity of the free-end of a tower positioned vertically on a hill, the airflow is parallel to the slope of the hill and has a turbulence intensity close to that of flat terrain. Turbulence intensity is the ratio of the root-mean-square of the velocity fluctuations, $u'$, to the mean flow velocity, $u$ [8]. Although the vertical component of turbulence intensity does change on encountering the windward side of a hill [9; 10; 11], this mechanism is not relevant to our study. In addition, as we report later in this paper, speed-up is not sensitive to changes in turbulence intensity.

#### *2.3.2 Calculating the Speed-up for a Tower on Sloped Terrain*

In order to calculate the speed-up for a tower on sloped terrain, we need only change the inlet and bottom face boundary conditions. Airflow now enters through the inlet and bottom faces, inclined at an angle to the horizontal equal to the terrain slope.

In addition to speed-up, there are other sources of measurement error associated with anemometers. One source of error, relevant to this paper, results from the fact that anemometers only measure the wind velocity component perpendicular to the main axis of the device, which is almost always vertical; this has implications for a met tower sited vertically on the windward side of a hill, subject to an uphill wind that is parallel to the slope. In this paper, the speed-up error can be understood as both the speed-up error in the actual absolute flow velocity above the vertical tower *and* the speed-up error in the velocity reported by the anemometer.

## 3 Results and Discussion

For all configurations of wind-speed, turbulence intensity and terrain slope, our simulations show a significant difference between speed-up errors for solid and hollow towers. The airflow around the top of solid towers appears to be less stable, with rapid, time-dependent, fluctuations which give rise to significant uncertainty in the determination of the speed-up error. We present results for our problem of a hollow tower with an anemometer located 2 diameters above the top.

### *3.1 Sensitivity to the Free-stream*

Most wind turbines operate at wind-speeds ranging from 8 to 12 m/s. In this range, the relative magnitude of the simulated speed-up is almost independent of the absolute magnitude of the free-stream wind-speed (speed-up is written as a percentage of the free-stream wind-speed). This independence can be seen in Fig. 5 - 7 for a free-stream turbulence intensity of 10%.

### *3.2 Sensitivity to Turbulence*

In the normal operating range of wind-speeds (8 to 12 m/s), the simulated speed-up appears to be also independent of the turbulence intensity of the free-stream (Fig. 8). This conclusion is based on two simulation runs with turbulence intensities of 10% and 15% and implies that the anemometer data can be corrected without any complications arising from turbulence in the airflow. Together with the previous observation (Section 3.1), we find that the speed-up can be associated with a particular anemometer set-up and is dependent only on quantities that can be determined (terrain slope, tower geometry, fluid properties and tower surface conditions).

### *3.3 Sensitivity to Sloped Terrain*

Airflow is accelerated when passing over a hill and, for this reason, wind farms are often sited on slopes. For practical considerations, these slopes never exceed 25°. Simulation runs at slopes of 0°, 15° and 25° indicated that, as expected, the speed-up has a significant dependence on terrain slope (Fig. 9 and 10). However, as can be seen in these figures, there is only a small difference between speed-up values from 0° through 60° (Fig. 3) for slopes of 15° and 25°. This leads to the practical suggestion that if the prevailing wind is up-hill and parallel to the hillside, speed-up dependence on slope can be minimised by installing the anemometer on the upstream side of the tower, between 0° and 30° on the circumference (Fig. 3).

### *3.4 Sensitivity to Tower Condition*

The surface roughness of the interior of the hollow tower is captured by the pipe friction coefficient $\lambda$, present in Eqn. 1. We ran simulations with $\lambda = 0.02$ and $\lambda = 0.05$, corresponding respectively to a very smooth and a very rusty tower. For the case of a tower positioned on level ground, with a free-stream wind-speed of 8 m/s and a turbulence intensity of 10%, there is a small dependence on $\lambda$ (Fig. 11). A more complete study may establish that for normal wind conditions, the pipe friction coefficient does not significantly affect the speed-up error. Careful selection of tower materials, along with regular maintenance and cleaning, will minimise variability in the condition of the tower and of any effect that the surface roughness (and debris) will have on the airflow through and around the structure.

In addition to the speed-up values for anemometers located 2 diameters above the top of the tower, we also recorded wind-speed values at various heights above the centre of the tower. The speed-up decreases as the distance above the tower increases. This is shown in Fig. 12 for a wind-speed of 12 m/s and a turbulence intensity of 10%. Engineers and technicians may find this plot useful when locating anemometers.

## 4 Conclusions

The aim of our investigation was to determine the measurement error due to speed-up for the specific case of an anemometer located 2 diameters above the top of a hollow met tower sited on level terrain. We found that the maximum error for this configuration is approximately 2% of the actual wind-speed (Fig. 5).

We found that the speed-up over the top of a hollow met tower depends only on variables that can be determined. Speed-up is independent of the absolute magnitude of the free-stream wind-speed and the turbulence intensity of the wind. The error depends on the geometry of the met tower, the slope of the terrain where the tower is sited and the condition of the tower.

We conclude that top-mounted anemometers should be located at the windward side of a met tower, where a particular wind direction prevails, and at least 5 diameters above the top. This will reduce speed-up to less that 1%. The IEA recommendation is for a minimum separation of about 6 tower diameters [12]. In line with the IEA's recommendation that the anemometer installation should be 'clean' [12], towers should be made from a corrosion resistant material and maintained and cleaned regularly to minimise flow disturbance.

## Acknowledgements

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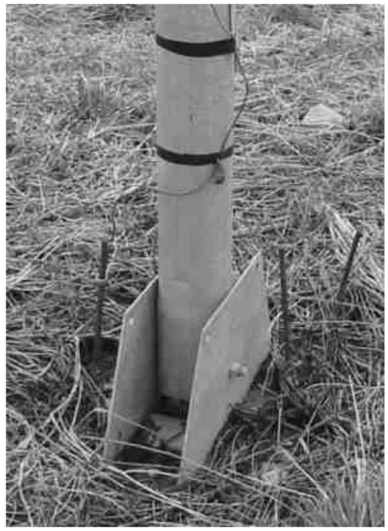

Fig. 1. The base of a typical hollow tower. The gap between the bottom of the tower and the base-plate is clearly visible.

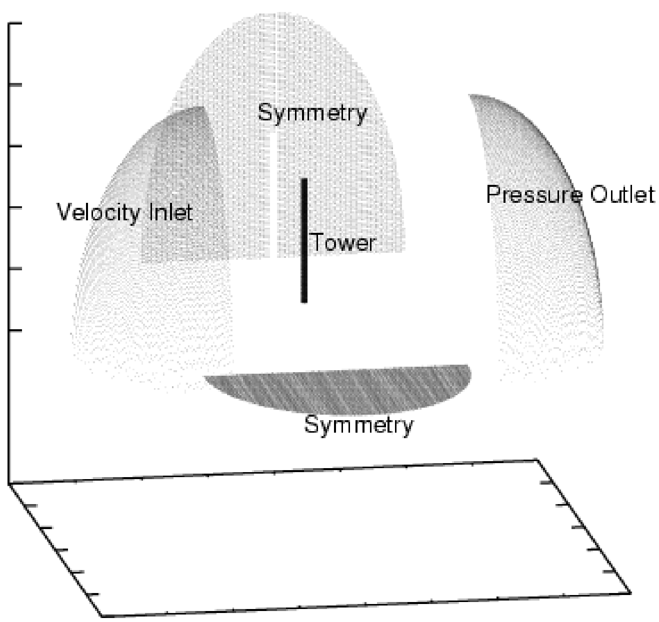


Fig. 2. The computational domain with exploded surfaces for illustration.

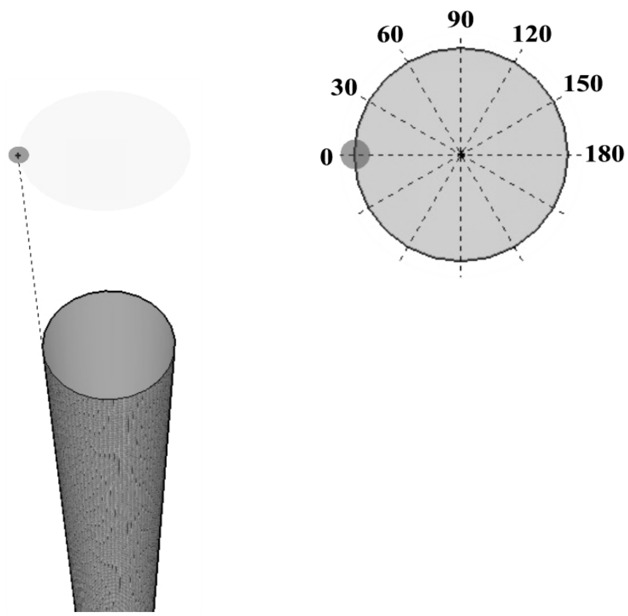


Fig. 3. Sample anemometer positions (in steps of 30°) around the circumference of the meteorological tower. The wind blows from left to right. The anemometer cups are located two diameters above the top of the tower.

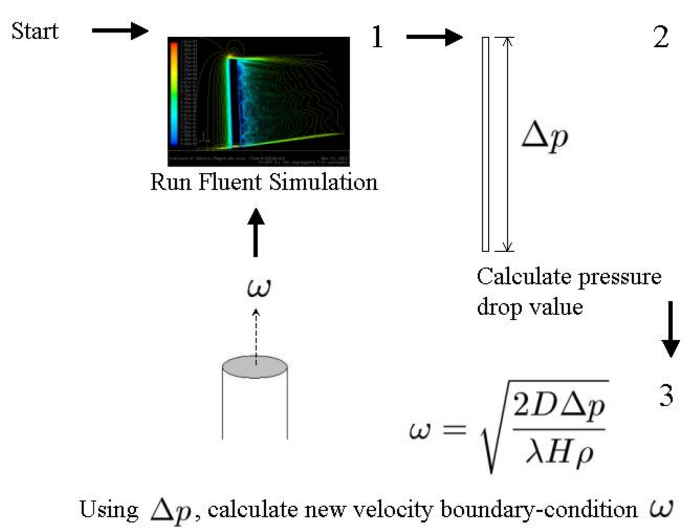


Fig. 4. The iterative process used to calculate the speed-up over a hollow tower. The process is repeated until $\omega$ converges to a fixed value.

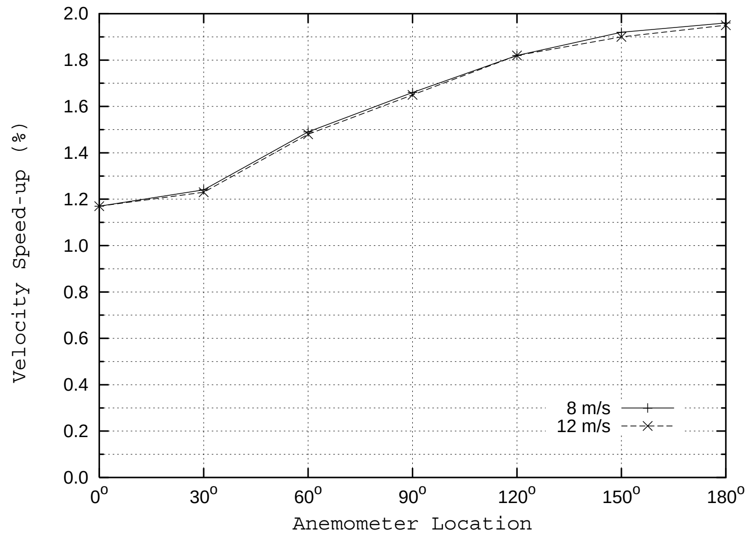


Fig. 5. Influence of the free-stream wind-speed for a hollow tower positioned on level ground and a turbulence intensity of 10%.

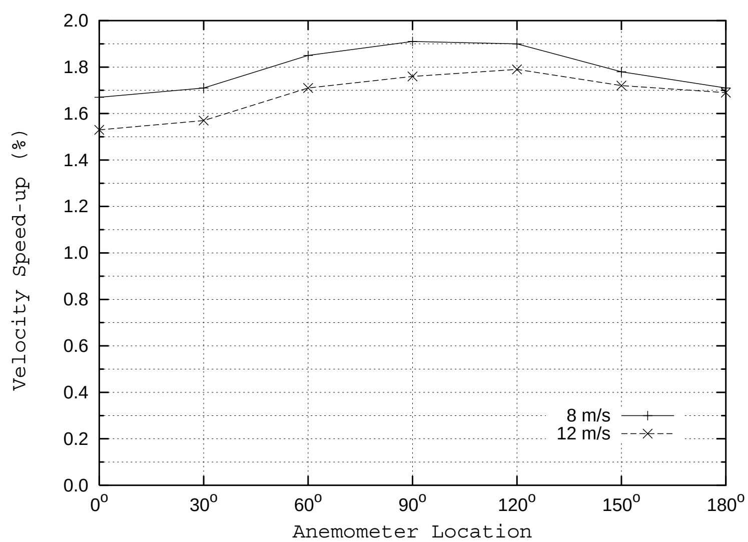


Fig. 6. Influence of the free-stream wind-speed for a hollow tower positioned on a slope of 15° and a turbulence intensity of 10%.

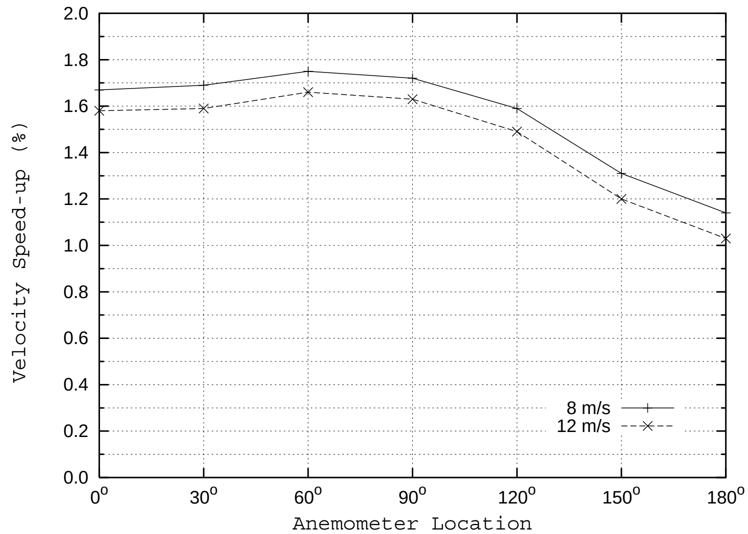


Fig. 7. Influence of the free-stream wind-speed for a hollow tower positioned on a slope of 25° and a turbulence intensity of 10%.

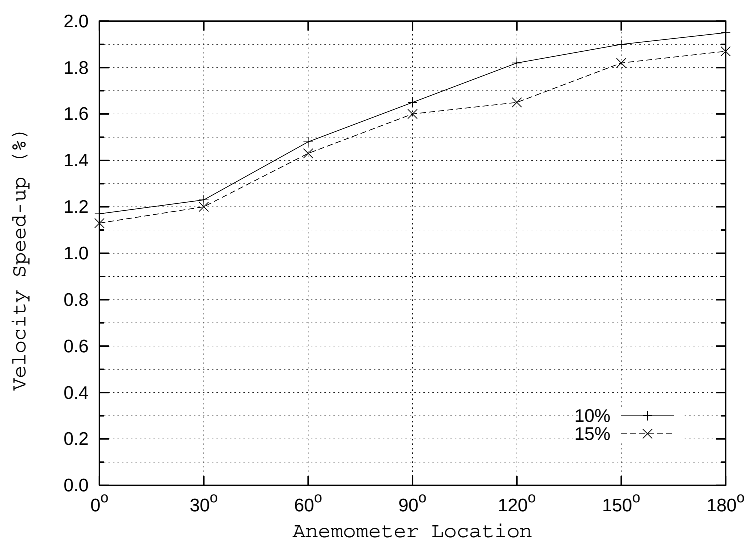


Fig. 8. Influence of the turbulence intensity for a hollow tower positioned on level ground and a free-stream wind-speed of 8 m/s.

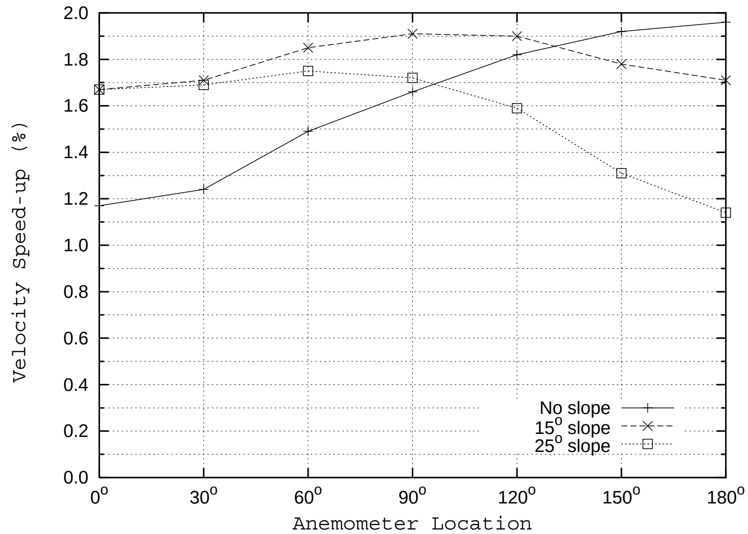


Fig. 9. Influence of terrain slope for a hollow tower in a free-stream wind-speed of 8 m/s and a turbulence intensity of 10%.

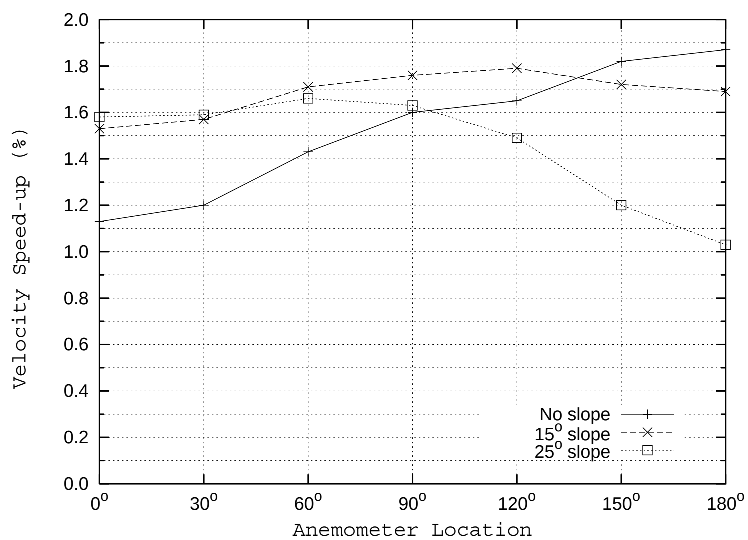


Fig. 10. Influence of terrain slope for a hollow tower in a free-stream wind-speed of 12 m/s and a turbulence intensity of 10%.

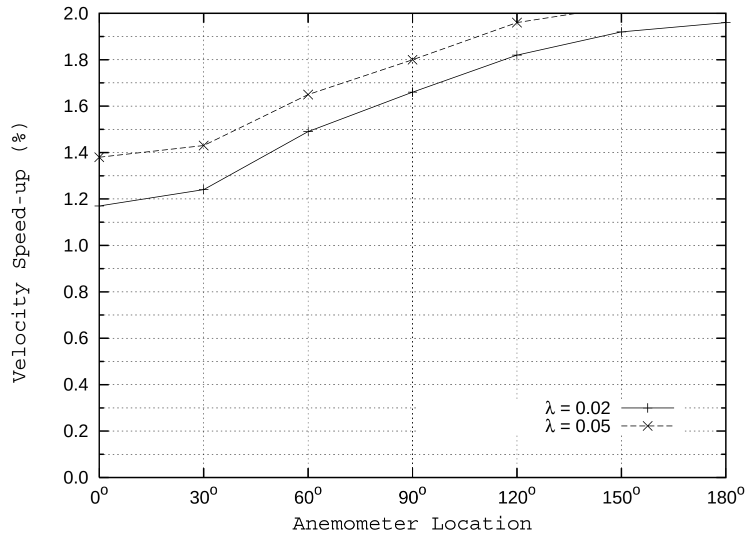


Fig. 11. Influence of the pipe friction coefficient $\lambda$ for a hollow tower positioned on level ground, a free-stream wind-speed of 8m/s and a turbulence intensity of 10%.

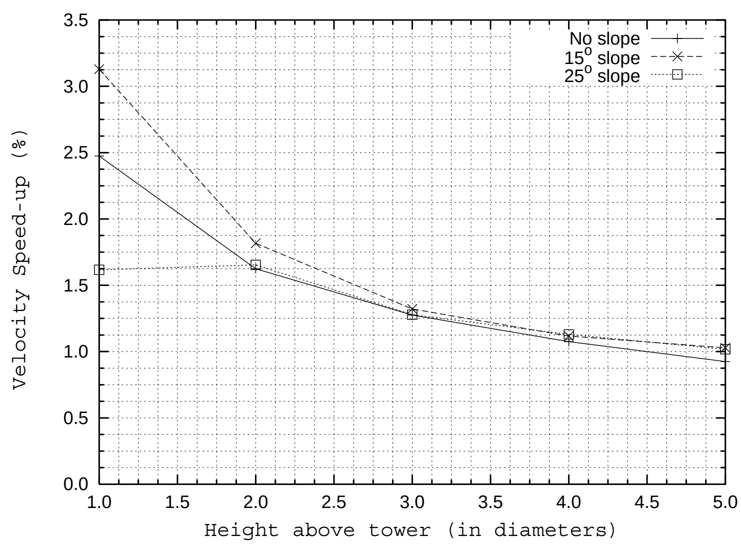


Fig. 12. Speed-up values at various heights above the centre of a hollow tower positioned on level ground.