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Experimental Determination of Reactions of Wind-Resistant Support of Circular Stacks in Various Configurations

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***Abstract*—**Higher capacities of power plants together with increased awareness on environmental considerations have led to taller height of stacks. It is seen that strong wind can result in falling of stacks. So, aerodynamic consideration of stacks is very important in order to save the falling of stacks. One stack is not enough in industries and power sectors and two or three stacks are required for proper operation of the unit. It is very important to arrange the stacks in proper way to resist their downfall. The present experimental study concentrates on the mutual effect of three nearby stacks on each other at three different arrangements, viz. linear, side-by-side and triangular. The experiments find out the directions of resultant forces acting on the stacks in different configurations so that proper arrangement of supports can be made with respect to the wind directionality obtained from local meteorological data. One can also easily ascertain which stack is more vulnerable to wind in comparison to the others for a particular configuration. Thus, this study is important in studying the effect of wind force on three stacks in different arrangements and is very helpful in placing the supports in proper places in order to avoid failing of stack-like structures due to wind.

***Keywords*—**Stacks, relative positioning, drag and lift forces, resultant forces and supports.

I. INTRODUCTION

STACKS are simply the hollow cylindrical, straight or tapered, vertical conduits through which the exhaust gas of any power or process plant is released to the atmosphere at some certain height from the ground. Exponential growth in demand for power in developing countries has led to a large number of thermal stations in the power sector. Higher capacities of power plants together with increased awareness on environmental considerations have let to taller height of stacks. Mono- and multi-flume stacks of heights up to 300 m are becoming common. Even though the circular stack is the simplest in structural shape, the challenge posed by the same in its analysis and design is enormous. Wind tunnel testing has long been recognized as an accepted design tool in the hands of engineers to solve many of the problems related to wind flow and wind-structure interaction. It has been rather difficult to conduct experiments at desired Reynolds number levels together with simulation requirements for atmospheric turbulence on models of stacks. Most of the analytical procedures and design equations available to date are based on semi-empirical approaches relying on data available from wind tunnel tests on models of stacks at low Reynolds number, and a few instrumented stacks in the field. Stacks are wind sensitive and undergo along wind response. In ordinary atmospheric conditions the drag experienced by stacks is very important to realize their stability analysis. Often in many countries it is seen that strong wind can result in falling of stacks. So, aerodynamic consideration of stacks is very important in order to save the falling of stacks. One stack is not enough in industries and power sectors for their proper operation. So often it is seen that two or three stacks are required for proper operation of the unit. It is very important to arrange the stacks in proper way to resist their downfall.

A good number of researchers have dedicated themselves in studying the effect of wind on stacks and chimneys. The mostly studied aspects of wind effects on stacks include the along-wind and crosswind responses either without obstruction or affected by obstructions. Determination of lift and drag forces acting on a single or a set of stacks is of primary importance in order to ascertain the effect of wind on the stability of the stacks. Reference [1] studied on the lift acting on tapered stacks way back in 1972. Wind load on chimneys were recorded by [2] in 1973. Reference [3], in 1976, have done full scale measurements on steel chimney stacks. A study on in-line chimney models has also been carried out by [4] in 1981. Reference [5] has also attempted to tackle the problem of in-line stacks with full-scale objects in 1984. The same year produced another work, this time by [6], on wind-induced oscillations of stacks. A recent work on drag of circular cylinders in atmospheric turbulence by [7] in 2004 highlights the advancement in this particular field of study. Different combinations of stacks will face different forces in different directions and it is the task of the designer to ascertain those in order to put the supports on the stacks properly.

The present experimental study concentrates on the mutual effect of three nearby stacks on each other at three different arrangements by finding out the magnitude and the direction of force experienced by each stack in order to take necessary guard to avert falling of such stacks. Three different

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arrangements of stacks that are chosen are namely (i) along wind linear arrangement, (ii) across wind side-by-side arrangement and (iii) triangular arrangement. An additional study has been incorporated wherein the atmospheric boundary layer is simulated for the sub-urban terrain and chimney models are designed accordingly before carrying out the same experiment in three same arrangements.

II. EXPERIMENTATION

The experimental study of the wind effects on stacks is carried out in the lower test section of the Jadavpur University Low Turbulence Closed Circuit Subsonic Wind Tunnel at different Reynolds numbers. Pressure measurements are taken with the help of a three-channel pressure-sensing module of SENSYM make with digital display. The stack models are made of wood and pressure tappings are provided on the circumference of the stacks from top to bottom in order to measure the surface pressure readings. The stack models are made maintaining a ratio of about 1:400 to the dimension of standard stacks in general. The diameter of stack models is 44 mm and height is 484 mm. This results in a blockage ratio of 3.78 %. The experiment is performed with three stack models in three different arrangements. Pressure taps on the models are connected to the pressure sensing modules through flexible pipes which are taken out of the test section of the wind tunnel through a small hole at the end of the test section. Pressure values are measured at different taps and different orientations of the models at different Reynolds numbers. The pressure coefficient C_p, drag coefficient C_D, lift coefficient C_L and total force coefficient C_F are calculated from the following expressions:

$$C_p = \frac{p - p_s}{\frac{1}{2}\rho_a U^2} \quad (1)$$

$$C_D = \frac{D}{\frac{1}{2}\rho_a U^2 A} = \frac{\sum C_{p_x}.\Delta A_x}{A} \quad (2)$$

$$C_L = \frac{L}{\frac{1}{2}\rho_a U^2 A} = \frac{\sum C_{p_y}.\Delta A_y}{A} \quad (3)$$

and

$$C_F = \frac{F}{\frac{1}{2}\rho_a U^2 A} = \sqrt{C_D^2 + C_L^2} \quad (4)$$

where p, p_s, ρ_a, U, C_{px}, C_{py}, ΔA_x, ΔA_y, A, D, L and F represent pressure at a particular tapping in Pa, static pressure at corresponding position in Pa, density of air at prevailing temperature in kg/m^3, free stream velocity of air in m/s, x-component of C_p, y- component of C_p, surface area around a particular pressure tap projected on x-plane in m^2, surface area around a particular pressure tap projected on y-plane in m^2, total projected area (same from any horizontal viewing direction) in m^2, Drag force in N, Lift force in N and Total Resultant of D and L in N respectively.

Figures 1, 2 & 3 show how the three stack models are placed inside the lower test section of the JU Subsonic Closed Circuit Low Turbulence Wind Tunnel. All three models are placed on a common wooden stand of small thickness but thick enough to hold the stacks in position while the wind flows. The models could also be rotated about their own axes in order to take pressure data at various azimuthal angles. The pressure readings are taken at four different Reynolds numbers in sub critical region, viz. 0.24e5, 0.67e5, 1.34e5 and 1.88e5. The readings are taken at an interval of 45 degrees azimuth. The gap between each of the stacks placed in line is kept constant at 50 mm. Different coefficients are calculated using the pressure readings on the surface of the stacks near their top, which is more exposed to high wind, and the abovementioned formulae. The pressure readings that are obtained are averaged over the height and are used to calculate the drag coefficient, lift coefficient and total force coefficient of each stack in various configurations.

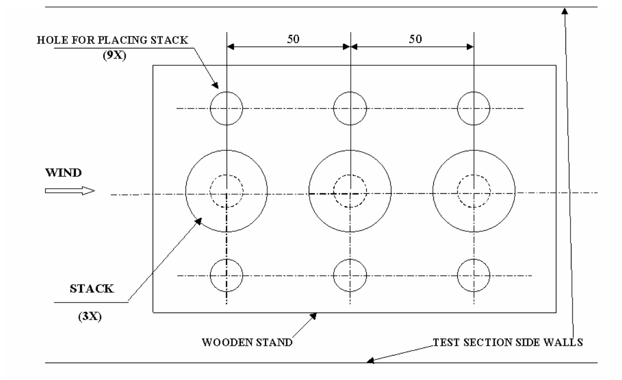

Fig. 1 Experimental Set Up for Stacks in Linear Along-wind Arrangement (Top View)

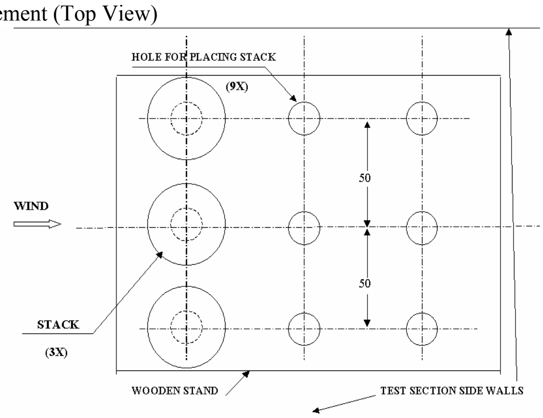

Fig. 2 Experimental Set Up for Stacks in Side-by-side Arrangement (Top View)

The atmospheric boundary layer for the sub-urban terrain (α = 0.28) is then simulated inside the same test section of the wind tunnel using the method suggested by Irwin[8] (1981). The models of reinforced concrete chimneys (average diameter = 16 mm, height = 122 mm, scale = 1:1000) are then designed as per the Indian Standard (IS 4998) so that they remain submerged inside the bottom 1/3rd of the simulated boundary layer and experiments are carried out as before in the same three arrangements of three chimneys.

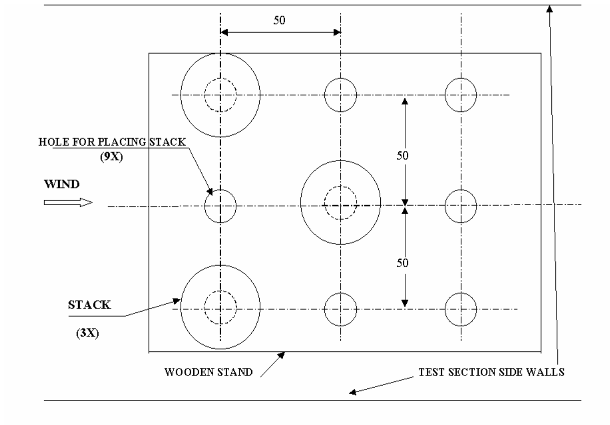

Fig. 3 Experimental Set Up for Stacks in Triangular Arrangement (Top View)

III. RESULTS & DISCUSSIONS

The plot [Fig. 4] of drag coefficient at different Reynolds numbers for the stacks in along wind linear tandem arrangement shows that the drag coefficient is highest for the middle stack, while it is the least for the stack at the back. The results obtained in validated using the data obtained by Ohya[7] for drag coefficient for smooth circular cylinders where the value of drag coefficient is around 1.2 in the same range of Reynolds number as in this case. The lift coefficient [Figure 5], however, is much less than the drag coefficient, front stack experiencing the maximum lift. Figure 6 indicates how the total force coefficient varies with Reynolds numbers for the stacks in the above-mentioned configuration. The result that comes out of this plot clearly indicates that for along wind linear arrangement the middle stack experiences maximum drag force due to wind. This result is validated with the predictions given in IS: 875 (Part 3) – 1987[9], which matches well with the front stack force coefficient data. Figure 7 is produced in order to show the angles that the total resultant force makes with the wind direction for different Reynolds numbers. This plot will be very helpful in order to place the supports to the stacks at correct place. Strong winds coming from a particular direction can be predicted from meteorological data and the direction of the resultant force may be estimated using the above-mentioned plot of angles at various Reynolds numbers and supports should be placed accordingly.

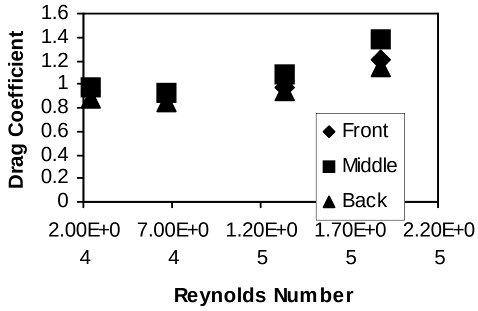

Fig. 4 Variation of Drag Coefficient of Stacks in Linear Along Wind Configuration

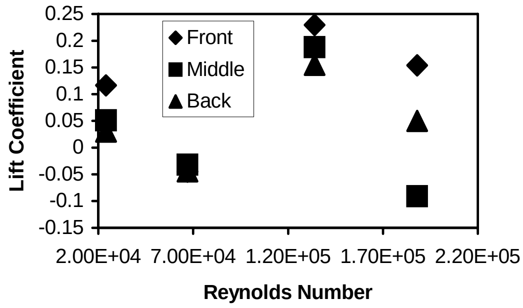

Fig. 5 Variation of Lift Coefficient of Stacks in Linear Along Wind Configuration

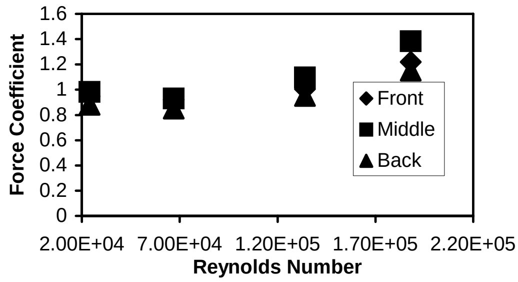

Fig. 6 Variation of Total Force Coefficient of Stacks in Linear Along Wind Configuration

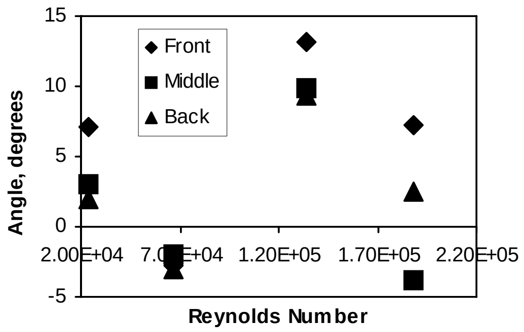

Fig. 7 Variation of Angle between Total Force and Wind Direction for Stacks in Along Wind Linear Configuration

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The fluctuation of drag coefficient with Reynolds number for stacks in side-by-side arrangement is plotted in Figure 8. It is seen that in this arrangement also the drag coefficient of the middle member of the three stacks is the highest, while the drag experienced by other two stacks is almost the same. Figure 9 shows how the lift coefficient varies with Reynolds number for stacks in side-by-side arrangement. It clearly indicates that the right stack experiences a considerable amount of lift from right to left, while the left stack experiences the same from left to right. However, the middle one experiences very little or almost no lift. The variation of total force coefficient with Reynolds number is also plotted for this arrangement in Figure 10. Here, it is evident that the stacks at the sides experience more force due to wind in comparison to the stack standing at the center. Figure 11, lastly, shows the variation of the angle made by the resultant force with the wind direction at different Reynolds numbers.

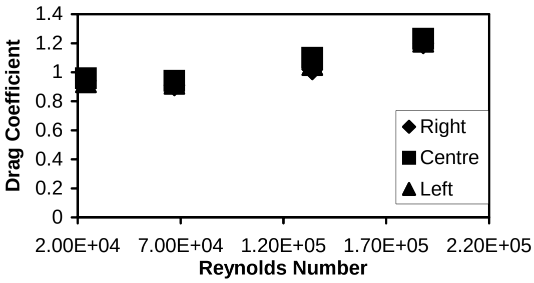

Fig. 8 Variation of Drag Coefficient of Stacks in Side-by-side Configuration

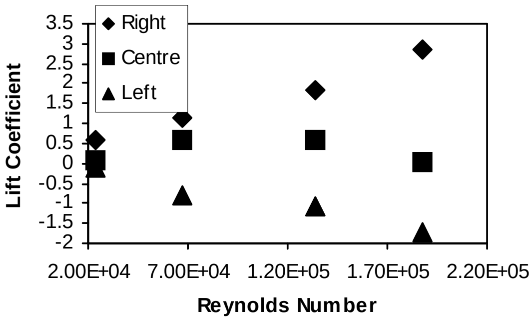

Fig. 9 Variation of Lift Coefficient of Stacks in Side-by-side Configuration

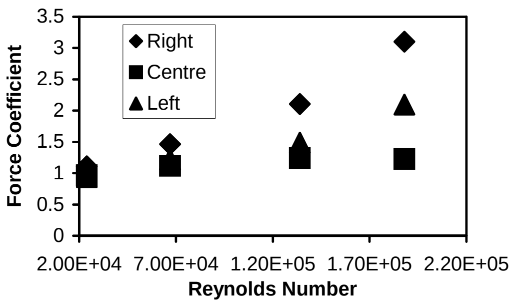

Fig. 10 Variation of Total Force Coefficient of Stacks in Side-by-side Configuration

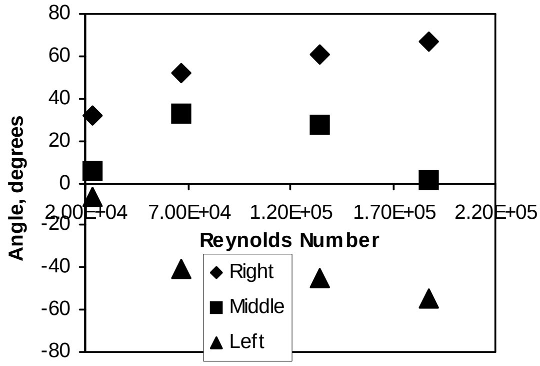

Fig. 11 Variation of Angle between Total Force and Wind Direction for Stacks in Side-by-side Configuration

Fig.12 depicts the variation of drag coefficient with Reynolds number for stacks in triangular arrangement, which indicates that the drag coefficient of the front stack is the highest amongst the three. The variation of lift coefficient, as is evident from Fig.13, gives a similar picture to that in case of side-by-side arrangement. Here also, the stack at the right corner of the triangle experiences considerable amount of lift from right to left, while the stack at the left corner experiences so in the opposite direction, and the stack at the apex experiences minimum lift. The plot showing the variation of total force coefficient with Reynolds number is given in Fig.14 for triangular arrangement. This result is once again validated with the predictions given in IS: 875 (Part 3) – 1987[8], which matches well with the front stack force coefficient data. Here, it is evident that the stacks at the side corners experience more force due to wind in comparison to the stack standing at the center. The variation of the angle subtended by the resultant total force with the wind direction, depicted in Fig.15, shows that the variation of the angle made by the resultant force with the wind direction at different Reynolds numbers is almost absent for a particular stack, although the value varies widely for the three stacks.

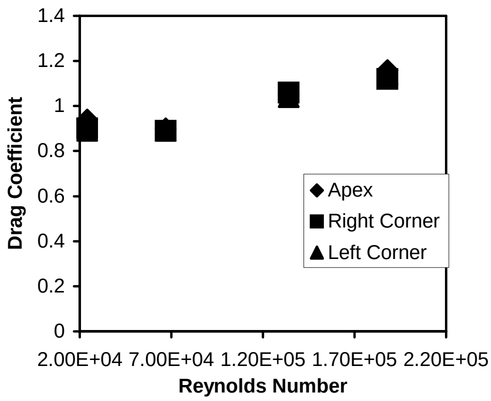

Fig. 12 Variation of Drag Coefficient of Stacks in Triangular Configuration

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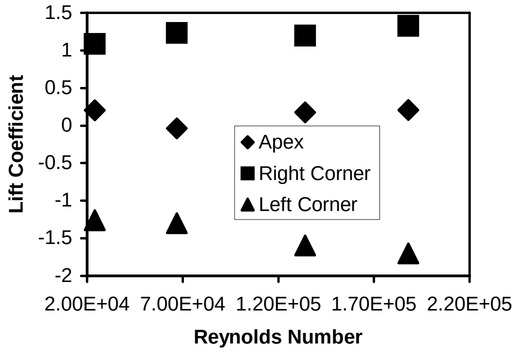

Fig. 13 Variation of Lift Coefficient of Stacks in Triangular Configuration

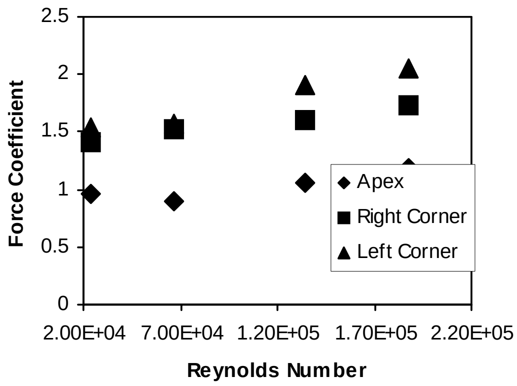

Fig. 14 Variation of Total Force Coefficient of Stacks in Triangular Configuration

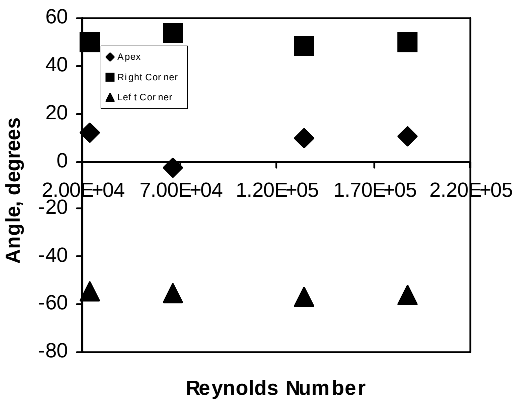

Fig. 15 Variation of Angle between Total Force and Wind Direction for Stacks in Triangular Configuration

Fig. 16 to 19 shows the variations of drag coefficients, lift coefficients, force coefficients and angles between the total force and wind direction inside the simulated atmospheric boundary layer. These results differ from the previous results mainly due to the change in flow and turbulence pattern inside the atmospheric boundary layer. The coefficients are found to have values of less magnitude than estimated previously.

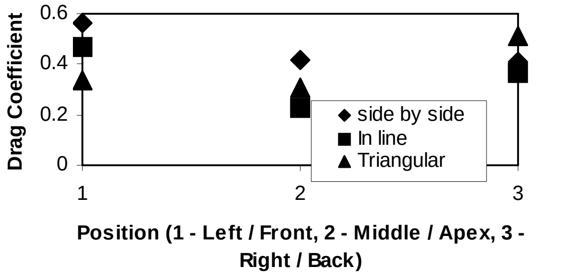

Fig. 16 Variations of Drag Coefficients inside Atmospheric Boundary Layer

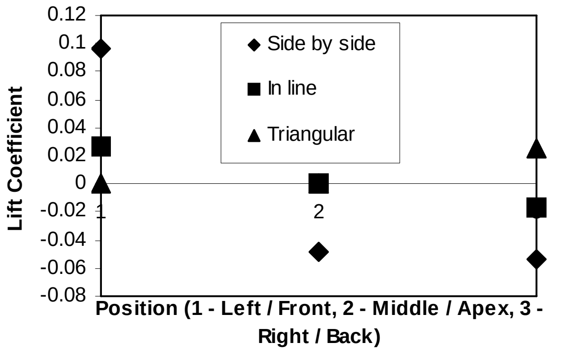

Fig. 17 Variations of Lift Coefficients inside Atmospheric Boundary Layer

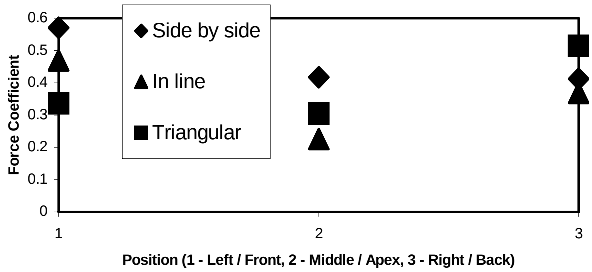

Fig. 18 Variations of Force Coefficients inside Atmospheric Boundary Layer

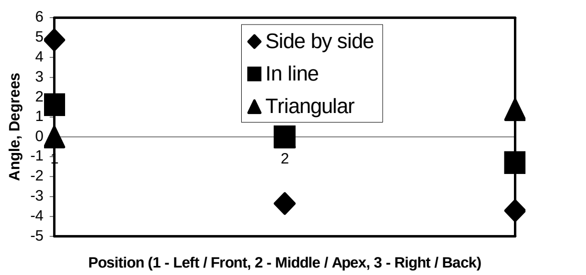

Figure 19 Variations of Angles between Total Forces and Wind directions inside Atmospheric Boundary Layer

IV. CONCLUSIONS

The experiments carried out under the purview of this study is mainly helpful to find out the directions of resultant forces acting on the stacks in different configurations so that proper arrangement of supports can be made with respect to the wind directionality obtained from local meteorological data. Besides, the other conclusions that can be drawn from these experiments are: (a) the second stack in along wind linear arrangement experiences the most drag and hence is much more susceptible to falling down with high gusts, whereas the last stack experiences the least drag and hence less prone to the downfall. (b) In side-by-side arrangement, although the middle one experiences maximum drag, the lift forces on the right and left stacks are far greater and hence the resultant forces on them are much more in comparison to the middle one. (c) In the triangular arrangement also, the lift force being so pronounced on the right and left corner stacks, the resultant force on them will be much higher in comparison to that on the front stack sitting at the apex of the triangle.

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