Design of Steel Chimneys: A Review

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Abstract

A chimney is meant for dispersing pollutants at high enough elevation; hence the first thing that has to be considered during the design process is the determination of its clear height and nominal diameter. The wind force exerted at any point on a chimney can be considered as the sum of a quasi-static and dynamic load components. These forces may be classified as: along wind force (drag) and across wind force (lift). In the present paper, design of steel chimneys has been reviewed on the basis of latest IS Codes. The review includes the basic design analysis of a chimney and the parameters such as height and diameter of the chimney. The forces of drag and lift, the gust load and the resultant load have also been calculated.

Key words: Ground level concentration of contaminants (GLC), draft, drag, lift

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1. Introduction

In addition of undertaking a comprehensive structural analysis the proper engineering of a chimney requires: a study of environmental aspects, estimation of aerodynamic and seismic forces, determination of thermal stresses as well as evaluation of alternative lining and insulation materials with due consideration of their cost, corrosion resistance and performance under different operating conditions. Thus the design of modern industrial chimney covers subjects like meteorology, thermal engineering, risk theory and chemistry etc. Steel chimneys are frequently called stacks [1].

2. Sizing Basic Dimensions

If the power output of the plant is less than 200MW, the required permissible minimum physical height is determined as per CPCB (Central Pollution Control Board):

$$H_S = 14 \cdot Q_P^{0.3} \qquad (1)$$

where H_s is the minimum physical height in meters and Q_p is the emission rate of SO_2 in kg/hr. If the stack height calculated above is less than the height of the surrounding building or nearby structure, then the minimum height is given by:

$$H_S = H_B + 5 \quad (2)$$

where, H_B is the height of the tallest building in a surrounding area of 150m radius.

2.1 Bureau of Indian standards (BIS) stipulations

The formulation adopted in the BIS code, IS: 6533 (Part I): 1989 is significantly different from the one which was recommended by the statutory authority. In the code two cases have been considered:

2.1.1 Consideration of draft

For a natural draft system the draft induced by a chimney, P_d in mm of water column is given by:

$$P_d = H(\rho_a - \rho_g) \quad (3)$$

where ρ_a = density of air at the design ambient temperature and pressure in Kg/m^3

ρ_g = density of gas at average temperature and pressure within chimney in Kg/m^3

If the exhaust system is equipped with forced or induced draft fans, the total draft is the sum of the natural draft and the pressure head created by the blowers. Hence, for forced or induced draft systems the total available draft at the base of the chimney can be found as:

$$P_d = H(\rho_a - \rho_g) + P_f \quad (4)$$

where P_f = pressure head induced by the blower.

Draft losses (IS 6533-I, 1989): Draft losses are the result of the dynamic head losses due to kinetic energy of gases leaving a chimney and head losses in overcoming friction along the internal surface of the flue. The losses from the inlet flange of the chimney up to the exit shall be considered while fixing up the height. Draft losses through the chimney P_{lc} in mm of water column may be calculated as:

$$P_{lc} = 2\frac{fHv_s^2}{gD}\rho_g \quad (5)$$

Draft loss due to kinetic energy at the exit is:

$$P_{le} = 0.5\frac{v_s^2}{g}\rho_g \quad (6)$$

The total draft loss is, therefore given by:

$$P_{lt} = P_{lc} + P_{le} \quad (7)$$

P_{lc}, P_{le} = draft losses as mentioned above,

f = fanning friction factor,

D = diameter of chimney in m.

The fanning friction factor f is a function of the Reynolds Number (Re) and the relative roughness (ε) of the flue duct surface. Values of f for different Re and ε are shown in Fig.1. The average values of roughness for uses in practical chimney design are given in Table1.

Table -1 Roughness values [6]

Flue duct material	Roughness (ε), mm
Riveted steel	2.75
Welded steel	0.05
Brick, concrete and plastered	1.60

The minimum draft that has to be available for satisfactory performances of a chimney is 0.006 inches (0.154mm) of water column [British

Standard]. Keeping this in mind the required minimum height from the point of consideration of draft is calculated from:

$$H = \frac{P_{net} - P_f + P_{le}}{\left((\rho_a - \rho_g) - 2\frac{fv_s^2}{gD}\rho_g\right)} \qquad (8)$$

2.1.2 Consideration of dispersion (IS 6533-I, 1989)

Assuming a relatively flat terrain and neglecting the temperature difference between the effluent and its surrounding, IS has suggested the following expression for finding the stack height from dispersion point of view:

$$H = \left(\frac{A.M.F.D}{8.C.V}\right)^{0.75} \qquad (9)$$

where, A =coefficient of temperature gradient of the atmosphere responsible for horizontal and vertical mixing of plume, (For tropical zone A=280, and for semi-tropical zone A=240)

M= estimated mass rate of emission of pollutants in g/s,

F = Dimensionless coefficient of rate of precipitation, Table 2

C = Maximum permissible ground level concentration of pollutants in mg/m^3 at STP, this may be taken as 0.5 mg/m^3 unless otherwise specified in relevant standards.

V = Estimated volume rates of emission of total flue gases in m^3/s

D = Nominal diameter in m.

While using Eq. (9) the following limitations have to be noted.

- The formula is applicable only in cases of tall stacks, the plume from which is free from interference with the air currents produced by nearby tall buildings.
- The formula assumes only a single source of air pollution. Where several stacks are located close to each other, the value of H obtained from the formula has to be increased such that the total ground level concentration at a place from the stacks for any particular pollutant does not exceed the air quality standards.
- The formula assumes the temperature of the gases to be equal to the atmospheric temperature. The resultant height of stack is slightly on the higher side.
- The maximum concentration as calculated above is reached at a distance X m from the chimney, approximately given by X=20H where H is the height of the chimney.

Table- 2 Coefficient F for use in Eq. (9) [2]

Efficiency of dust catching	Coefficient F
≥ 90	2.0
75 to 90	2.5
≥ 75	3.0

The nominal diameter of the stack has to be determined next to its physical height. If the quantity of flue gas to be handled is Q_g and permissible stack exit velocity is V_s (20 to 30 m/sec), then the inside diameter D is given by:

$$D = \sqrt{\frac{4Q_g}{\pi\, v_s}} \qquad (10)$$

3. Analysis of Design Loads

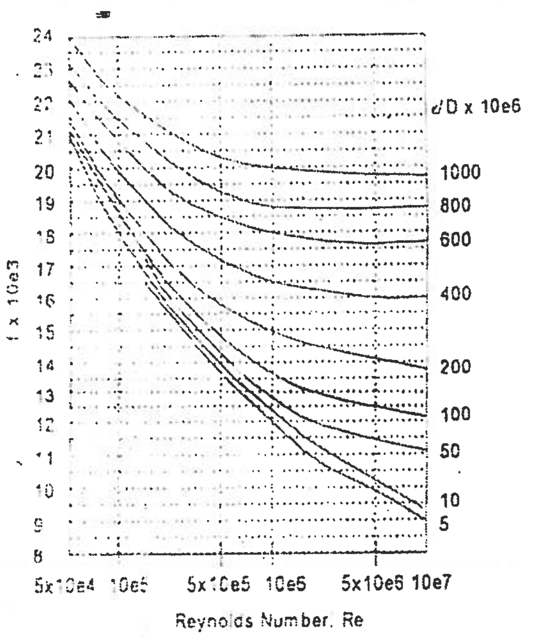

Figure 1
Friction factor f vs. Reynolds Number Re [7]

Once the basic physical dimensions (height and diameter) are determined analysis of the various loads acting on the chimney shell have to be considered. Chimney is a wind structure, i.e. it is a structure in whose design wind plays the major role. The forces on a chimney due to wind are classified as [4, 8, 9]: a) Along wind force (drag) b) Across wind force (lift). In the analysis, the along wind force is assumed to be composed of a quasi-static force component, which wind will exert if it blows with a mean constant velocity and a gust load.

Along wind Force = Drag Force + Gust Load

The static load component is that force which wind will exert if it blows at a mean speed and which will tend to produce a steady displacement in a structure. Wind exerts a static force on a bluff body obstructing its flow. The distribution of wind pressure around the circumference of such a body depends on its shape and direction of wind incidence. Such pressure causes circumferential bending of large-diameter chimneys. In addition, drag produces along-wind shear force and bending moments that the chimney fabric has to safely withstand. The total drag force acting on the projected area A normal to wind direction defined by coordinates z_1 and z_2 is given by

$$F_d = \frac{1}{2}\frac{C_d \rho_a}{2n+1}\left(\frac{U_0}{Z_0^n}\right)^2 D\left(z_2^{2n+1} - z_1^{2n+1}\right) \quad (11)$$

Where, F_d = drag force, N

C_d = drag coefficient

ρ_a = density of air, kg/m^3

A = projected area, m^2

U_0 = wind speed at reference height Z_0, m/s

n = an exponent which essentially depends on surface roughness

Table- 3 Value of exponent n [5]

Stability Class	Urban Conditions	Rural Conditions
Extremely unstable	0.10	0.07
Moderately unstable	0.15	0.07
Slightly unstable	0.20	0.10
Neutral	0.25	0.15
Slightly stable	0.40	0.35
Stable	0.60	0.55

The gust load depends on the natural frequency in the fundamental mode, wind speed, terrain category, clamping and size of the chimney. Expressions for calculating the gust load are found by considering the spectral density function. The gust load component at any section is given by:

$$F_g = C_d A \rho_a u \sqrt{\int_0^\infty S_n dn} \quad (12)$$

$$S_n = \frac{C_f U_0^2}{n} \frac{4x^2}{\left(1+x^2\right)^{4/3}} \quad (13)$$

$$n = x \cdot \frac{U_0}{1220} \quad (14)$$

Where, S_n = spectral density at frequency n

n = frequency in, Hz

C_f = terrain friction drag coefficient, Table 4

Table- 4 Terrain surface parameters [7]

Category	Description	C_f
1.	Large cities and built up area	0.050
2.	Rough wooded country, and city outskirts	0.015
3.	Flat open country, open flat coastal belts	0.005

The total gust load acting over any section of chimney can be found by Eq. (15)

$$F_g = 2.18 U_0^2 C_d D . \rho_a \sqrt{C_f} \frac{1}{Z_0^n} \frac{1}{n+1} \left(z_2^{n+1} - z_1^{n+1}\right) \quad (15)$$

The alternate shedding of vortices cause a transverse force called lift. Experimental observations show a wide scatter in the form of the lift forcing function. However, for practical design purpose

$$F_l = \frac{1}{2(2n+1)} C_l \rho_a \left(\frac{U_0}{Z_0^n}\right)^2 D\left(z_2^{2n+1} - z_1^{2n+1}\right) \quad (16)$$

Where F_l is the amplitude of the uniformly distributed crosswind force (in N/m) of chimney height and C_l is the dynamic lift coefficient. Depending on the Reynolds number, Re, the dynamic lift coefficient for a cylindrical cross section may reach up to about 0.7 when Re has a value of 10^5. If the Reynolds number is calculated for any particular wind velocity, a reasonable value of C_l may be determined using Figure 2. It has been emphasized that there is no definite value of C_l which can be taken as corresponding exactly with any particular value of Re.

The total along wind force is the algebraic sum of the static drag force F_d, Eq. (11) and the gust load F_g, Eq. (15). The resultant design force which acts at any cross section is the vector sum of the along wind forces and the across wind force.

$$F = K_1 \sqrt{\left(F_d + F_g\right) + rF_l} \quad (17)$$

Where r is the dynamic magnifier at the design wind speed and k_1 is the overload factor, which takes into account the uncertainties in loading. The resulting bending moment at any cross-section at a distance z from the base of the chimney due to wind loads is given by:

$$M = F \cdot \frac{H-z}{2} \quad (18)$$

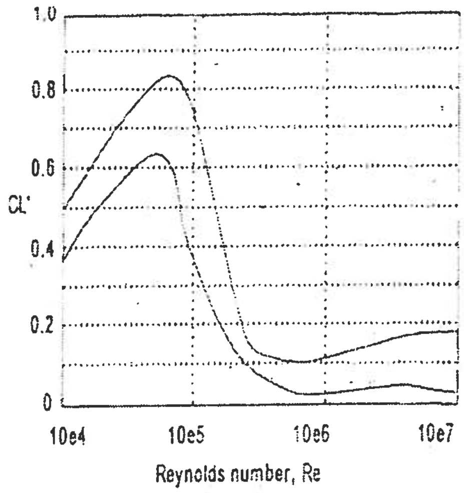

Figure 2 Dynamic lift coefficient [7]

According to Bureau of Indian standards the temperature effect is accounted by considering the most adverse temperature to which the chimney may reasonably be exposed. The anticipated reduction in the allowable working stress shall be obtained by multiplying the basic stresses, due to wind or earthquake plus self weight, by a temperature coefficient K_t given below (IS6533-II, 1989).

Table- 5 Variation of temperature coefficient with temperature [3]

Temp., 0C	0-200	250	300	350	400
K_t	1.0	0.75	0.67	0.6	0.5

It is also recommended to keep the wall temperature of the shell below 400°C. The self weight of chimney along with the weight of accessories, such as ladder, platform etc. need to be considered as it will add up with the bending stress induced by wind loads. The final design forces are arrived at by combining the forces due to [3, 8]:

1. Dead loads + temperature load + service loads on platform + wind load.
2. Dead loads + temperature load + service loads on platform + seismic load.

It has to be noted that, wind and seismic loads should never be considered to act simultaneously, as otherwise the design become extremely conservative.

4. Conclusion

In the present paper, chimney height and diameter have been calculated from draft requirements and from environmental regulations too. Conventionally, a circular cross-section is the most popular choice for a stack cross section. It is partly because of easiness in construction and partly because of convenience in structural design against wind loads [10]. After this drag force, lift force, gust load and resultant load have been calculated. Accessories required for safe operation and maintenance are designed based upon the regulations of CPCB and Indian Standards. Accessories required are aviation warning lights, ladder, maintenance platform, flue opening, lightening conductor and tuned mass dampers etc [6]. Finally chimney is painted with heat resistant high temperature aluminium paints from inside as well as from outside.

References

1. H. Edwin Gaylord and Charles Gaylord, "*Structural Engineers Handbook*", McGraw Hill Publishing Co., 3rd Edition, pp.30.1-30.25.

2. Bureau of Indian standards, "Design and Construction of Steel Chimney Code of Practice, Mechanical Aspect" IS: 6533-1989 (Part 1), Reaffirmed 2006.

3. Bureau of Indian Standards, "Code of Practice for Design and Construction of Steel Chimney, Structural Aspect" IS: 6533-1989 (Part II), Reaffirmed 2003.

4. Claes Dyrbye and Svend O. Hansen, "*Wind Loads on Structures*", John Wiley & Sons, pp. 49-106, 1999.

5. "Assessment of Impact to Air Environment: Guidelines for Conducting Air Quality Modeling", Central Pollution Control Board, Delhi, Probes/ 70/ 1997-98.

6. K Klaus Kaemmer, et al., "The CICIND Chimney Book", Comite International Des Cheminees Industrielles (CICIND), pp. 66-76, 361-364, 2005.

7. S N Manohar, "*Tall Chimney Design and Construction*", Tata McGraw-Hill, New Delhi, 1985.

8. S K Agarwal and P Lakshmy, "Computer Analysis of Tall Free Standing Chimney", Journal of The Institution of Engineers (India), Vol. 74, pp187-196, Feb1994.

9. Giovanni Solari, "The Role of Analytical Methods for Evaluating the Wind-Induced Response of Structures", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 90, issue 12-15, pp1453-1477, Dec2002.

10. W Schneider, "Design of Steel Chimneys", Advances in Steel Structures, pp1269-1276, 2005.