EXPERIMENTAL INVESTIGATION OF FORCED CONVECTIVE HEAT TRANSFER IN UNLINED SINGLE FLUE CHIMNEY

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Abstract

Forced chimney draught tends to increase heat transfer from short chimney. Mixed convection along with inner spleen cylindrical pipes decreases the Peclet number and achieve higher Nusselt Numbers thereby increasing the exit velocity. The aspect ratio plays an important role in achieving wider dispersion and lower GCL. AL7075 T6 having high corrosive resistance, high shear and weight bearing capacity is considered for outer core of the chimney cylinders. Convergent angle of 20^0 is having maximum heat transfer rate. Experimentation is conducted on 400 mm length Al alloy of 40 mm diameter with varied air inlet ranging from 2 m/s to 20 m/s. Temperature v/s distance plot identifies the minimal height of the cylinder for optimal heat transfer under Normal and Forced Convection. Max6675 Thermocouples (K type) are evenly spaced along the cylinder to identify the distribution along the chimney. The sensor data is logged in Ms Excel for easy plotting. The results are intriguing and optimal height of 396 mm at 40 mm diameter. The differential heat transfer observed between natural chimney draught and blower assisted forced convection at 20 m/s is found to be maximum with exit velocity of 8.9 m/s.

Index Terms: **Chimney draught, convection, Peclet Number, Rayleigh Number, Nusselt Number, Spleen Pipes**

1. Introduction

Chimneys are tall and slender structures, used to discharge or exhaust off gases generated during combustion of fuel and assist in dispersing flues gases at higher altitude/ elevation with sufficient exit velocity. Care should be taken to increase the spread of the flue gas emissions owing to lower ground concentration/ sedimentation level (GCL) reaching the ground within pollution control board standards. Chimney diameter is dictated by the escape velocity of the flue gases whilst height is governed by plume gas dispersion etc. A taper in 1:50 to 1:100 is usually selected considering wind loading and seismic stability criteria. The chimney taper angle can be varied between 5^0 - 15^0. At higher convergent angle, higher heat transfer rate could be achieved [1]. Higher Convergent Angle, tend to increase pressure drop and thereby increase in Nusselt Number. Moreover, a correlation of Nusselt number, Rayleigh number and aspect ratio ($h/d > 5$) is proposed by[2] . At the low Rayleigh number, the Nusselt number increased with the increment of the convergent angle and vice versa.

Conventional wisdom says; heat transfer rate can be enhanced either by increasing the cross sectional area or by increase in temperature gradient or combination of both. Spleen pipes increase the cross sectional area. Turbulent flow with elevated Nusselt Number, increases the pressure drop and temperature gradient. The exit velocity of the flue gases is increased as well. Lower Peclet number is often observed in wavy surfaces or spleen type cylindrical structures. Design Codes - IS:4998, IS:6533 along with Supplementary Codes - IS:456, IS:800 , IS:875 (Part3 : wind loads), IS:1893 are considered in this paper.

The paper aims at experimental investigation of finding optimal height & diameter of cylinder with outer core made of Al7075 T6 alloy and inner core of Stainless Steel. The Pollution Control Board specifies a minimum height of 4.85 m above ground level (AGL) from highest structure of the installation. In this paper, we propose to investigate the heat transfer rate under forced convection using spleen pipe for 460 mm pipe length.

2. Problem Definition

Rapid industrialization, depleting natural resources, extensive usage of plastic materials are having adverse impact on the environment. The pollution control norms specify implementing land fill, storage bays, desulphation plant etc. as some of the measures to curb the carbon footprint of industries. Medium – Small & Micro Enterprises (MSME) sector contribute to more than 80% of manufacturing production capacity of the country. Individual states and nation-wide adherence to pollution control norms are mandatory for setting up the industries/ organizations; unfortunately they are not implemented in true spirit. Desulphation plants eliminate most of sulphur & harmful gases from the flue gases and emit only low intensity pollutants into the atmosphere. Though, commissioning of de-sulphation plants, incinerators etc. are capital intensive; they must be done to curb environmental impact. In this paper, we are investigating finding the optimal height and diameter of the chimney channel.

The core diameter of cylindrical pipe is inversely related to the exit velocity i.e. higher the diameter of cylindrical pipe the lower the exit velocity. Moreover, the longer the cylindrical pipe, the lower the exit velocity. The longer the cylindrical pipe, the more the corrosiveness & sediment formation on the inner cylindrical walls. The exit velocity directly relates to dispersion and higher the velocity; greater the shearing of the cylindrical walls. Under normal conditions; the heat transfer is purely owing to buoyancy of plume gases. The temperature gradient of plume gases, dictates the exit velocity and dispersion.

The importance of chimneys relies in dispensation of flue gases. Buoyancy dictates the longevity of the chimney under consideration. The higher the temperature gradient between inlet & outlet of the chimney; the greater the buoyancy – the greater the pressure difference between inlet and outlet and hence chimney draught carries the flue gases with enough exit velocity. If the temperature is less; then the flume gases tend to re-circulate within the chimney column thereby causing sedimentation; corrosiveness in the chimney column. The principle reason for chimney failure is due to corrosive nature of the flume gases.

Thermal analysis of the chimney column with enough chimney draught can be considered under steady state and natural convection with almost uniform boundary layer. Unfortunately, variance in pressure difference can be observed along the length of chimney column thereby Transient Flow, Unsteady State Analysis need to be looked after. The condensation of flume gases is yet another important factor affecting the Heat Transfer in chimney column.

As length of the column increases, the induced vibration due to wind loading plays an important role. Though, only any one of the wind loading or vibration loading is considered in analysis. The wind is assumed to be flowing at 18 kmph in a stable state throughout the chimney column. The vortex induced vibration at the chimney tip is countered by constructing spiral stairs at the top of the chimney column. Henceforth, correlation need to be derived between exit velocity, temperature gradient, heat transfer, length of the column, turbulence promoters etc.

Dimensionless numbers elucidate on the thermal state of the flue gases in the cylindrical column. Heat Transfer rates are directly related to Nusselt Number, Reynolds Number, Prandtl Number and Grashoff Number. Indirectly related to Strouhal number and Peclet Number. The lower the Pectlet Number; the greater the exit velocity and greater the heat transfer possible.

3. Vortex formation:

When wind flow crosses the chimney, vortices are shed alternatively from the sides causing pressure drop. Such pressure changes at regular intervals cause a lateral force perpendicular to the direction of wind. Vortex formation depends on Reynold's number (Re). Re_s ratio of wind inertia force to viscous drag force. Reynold's number < 3 x 10^5 (sub critical range). If Reynolds's number is between 3 x 10^5 and 3 x 10^6 (super critical range). Vortex shredding Frequency, f = SV/ Dα. Here, 'S' strouhal number (=0.2 for Re < 2 x 10^5), V is wind velocity (m/s) and Dα = critical outside diameter of chimney (i.e. diameter at 1/3rd height from top).

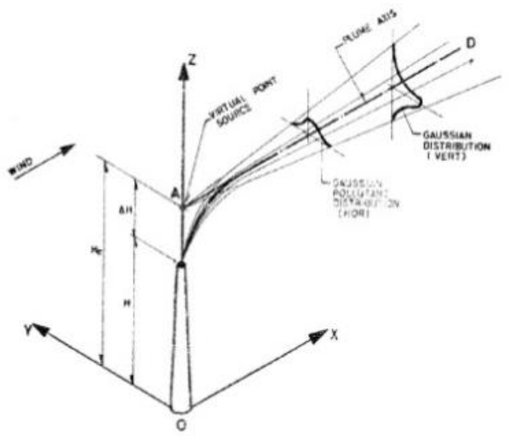
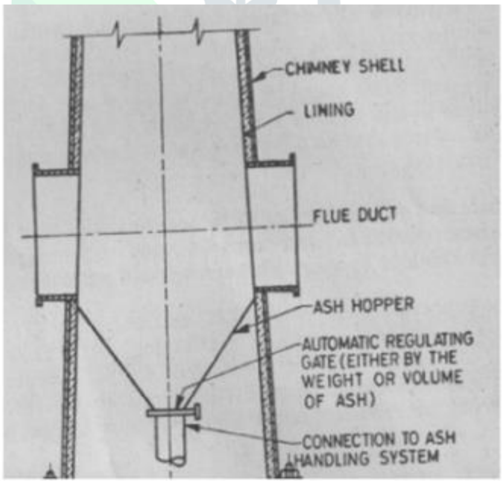


Fig. 2.2 Spread of a Plume



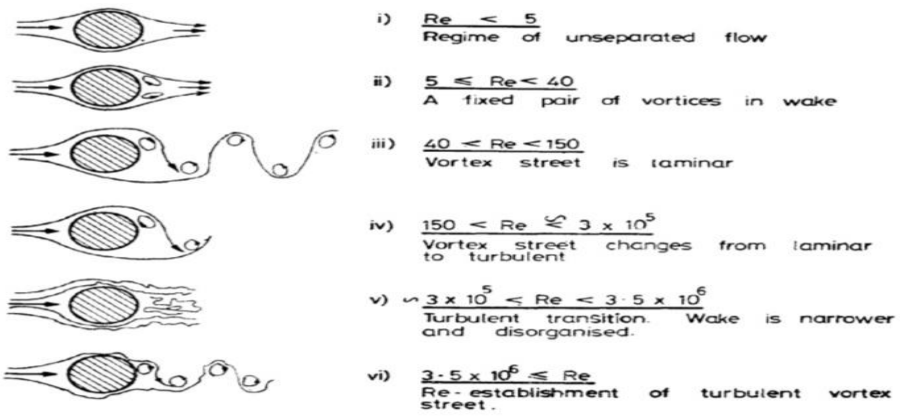


Fig. 3.5 Regimes of Fluid Flow Across Circular Cylinders

4. Heat Transfer by Chimney

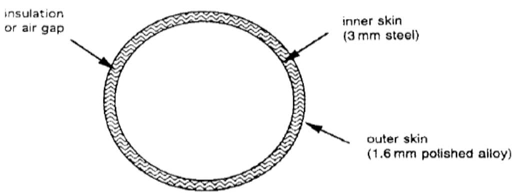


Figure 11.1 Chimney cross-section

Stage I	: Convection	->	Flue gases to inner chamber of the chimney
Stage II	: Conduction	->	from inner wall to outer wall of chimney if solid chimney
	Convection	->	if there is air gap between inner and outer walls of Chimney
	Radiation	->	if air gap between inner & outer walls of chimney
Stage III	: Convection	->	from chimney outer wall to atmosphere

These processes can be represented thus:

$Q = h_iA_i(t_g-t_{si})$

$Q = h_fA_f(t_{si}-t_{so})$ (1)

$Q = h_oA_o(t_{so}-t_o)$

where

Q is the heat flux (W)

h is the heat transfer coefficient ($W/m^2/K$)

A is the area (m^2)

t is the temperature (°C)

Subscripts:

f: fabric

g: gas

i: inside

o: outside

s: skin

In equation (1) the heat transfer across the fabric has been expressed in terms of a fabric heat transfer coefficient, h_f, and a cross-sectional area, A_f, over which this operates. The contributory terms to (h_fA_f) depend on the construction of the chimney. The above equations can be summarized giving:

$$Q\left(\frac{1}{h_iA_i}+\frac{1}{h_fA_f}+\frac{1}{h_oA_o}\right)=\left(t_g-t_o\right) \quad (2)$$

- The rate of heat transfer is conventionally represented in the form:

$$Q = U_oA_o\,(t_g-t_o) \quad (3)$$

- Where,
  - U_o represents the overall heat transfer coefficient for the exchanger and
  - A_o represents the area which is associated with it.

Any of the three area A_i, A_f or A_o could be used for this purpose, but here the outside surface area of the chimney (the largest of the three) has been used. An expression for the overall U-value of the chimney is obtained by dividing equation (2) by equation (3).

$$U_o = \frac{1}{\frac{A_o}{h_i A_i} + \frac{A_o}{h_f A_f} + \frac{1}{h_o}} \qquad (4)$$

If the chimney is of circular cross-section and does not have an appreciable taper, the areas in the above expression are given by:

- $A_o = 2\pi r_0 L$
- $A_i = 2\pi r_i L$
- $A_f = 2\pi(r_0 - r_i)L/ \ln(r_{0/} r_i)$

where L is the length (height) of the chimney.

If the thickness of the insulation/fabric is small compared with the radius, then equation (4) simplifies to that of one-dimensional heat transfer with all the areas being equal. The expression for the U-value is then:

$$U = \frac{1}{\frac{1}{h_i} + \frac{(r_o - r_i)}{k} + \frac{1}{h_o}} \qquad (5)$$

where k is the thermal conductivity of the gas. Above expression is generally sufficiently accurate for most practical purposes. For convenience, we can replace (r_o- r_i) with x, the thickness of the fabric layer. A common configuration for chimneys of less than 15 m height is to have an outer skin of aluminum alloy, with a low-emissivity surface, combined with a steel inner lining with an air gap of around 6 mm between the two metals. The heat transfer across an air gap is affected by the emissivity of the surfaces and the width of the gap. In general, the thermal resistance of an air gap increases with its width, but the value remains substantially constant at separations greater than 20 mm.

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \qquad (6)$$

Most gases have a value of Pr of about 0.74, and this value is substantially independent of temperature, hence equation (6) simplifies to;

$$Nu = 0.02\, Re^{0.8}$$

and the coefficient of heat transfer is obtained knowing the diameter of the tube, d, and the thermal conductivity of the gas, k.

Temperature Distribution in the Chimney

In order to evaluate the overall heat transfer from the flue to the surroundings it is necessary to take into account the flow pattern of the two fluids concerned, i.e., the flue gases rising in the flue and the air flowing over the outside of the chimney. The latter can be considered as being at a constant temperature t_o, hence we can construct an energy balance about a short section of the chimney:

$$dQ = -U(t - t_o)\, dA \qquad (9)$$

$$dQ = Wdt \qquad (10)$$

Where dA represents the surface area of the small section under consideration and dt is the small temperature drop of the flue gases in this section. The term W represents the thermal capacity rate of the flue gas, and is obtained by summing the product of the mass flow rate and specific heat for

$W = \sum(mc_p)$ kw/k

Evaluation of this expression can be a bit time-consuming. However, an approximate value of 1.476 $kJ/m^3/K$ can be assumed for the volumetric specific heat of the flue gas which, when multiplied by the volume flow rate of the gas (m^3/s) gives a value for W. The volume flow rate of flue gas can be estimated from the gas velocity and the internal cross-sectional area of the chimney. Equation (9) is a rate equation and equation (10) is an energy balance on the gas in the control volume; note that in these equations, heat lost from the gas is treated as a negative quantity. Eliminating dQ from these equations gives:

$$-U(t-t_o)dA = Wdt$$

By Rearrange:

$$-\frac{U}{W}\int_0^A dA = \int_{t_1}^{t_2} \frac{dt}{(t-t_0)}$$

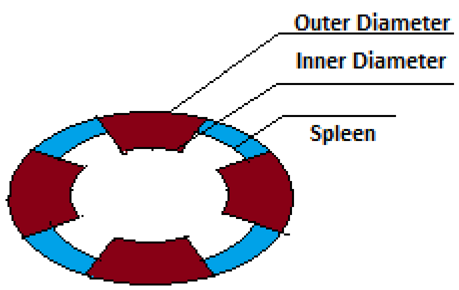
$$\Rightarrow \quad -\frac{UA}{W} = \ln\frac{(t_2-t_0)}{(t_1-t_0)}$$

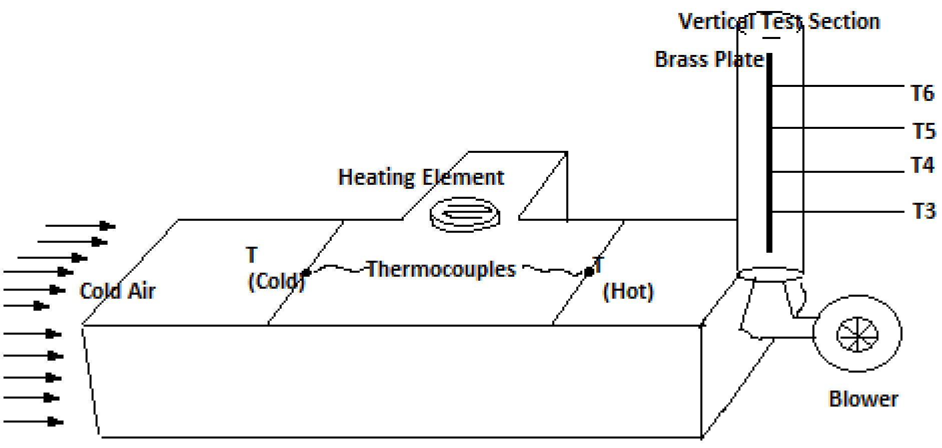
$$\Rightarrow \quad t_2 = t_0 + (t_1 - t_0)e^{-(UA/W)} \qquad (11)$$

This expression gives the flue gas temperature t_2 at the outlet of a section of the flue of area A, from a starting temperature of t_1. It is most appropriately applied to the entire flue but the expression can be solved for any number of flue section, so giving a temperature distribution along the flow path. As the thermal capacity rate of the flue gas is quite high, the ratio UA/W is generally small, giving a low temperature drop in the flue gas as within the chimney. The main function of the chimney insulation is to keep the temperature of the gas high by limiting the temperature drop between the gas and the inner lining of the chimney. In the steady state, the ratio of the temperature drop across the inner boundary layer to the overall temperature difference between the gas and the outside air is equal to the ratio between the thermal resistance of the inner boundary layer to the resistance of the entire chimney wall.

5. Experimental Setup

a. **Vertical Test Section:** An aluminum (AL7075 T6) test section of 60 mm diameter outer diameter and 50 mm inner diameter with internal spleens of 5 mm x 5 mm x 460 mm is fixed vertically to the ground. A heated coil (1000W/ 220V, 1Φ AC) is placed in the duct and heated air is blowed into the vertical test section using 1Φ - 220V/ 0.25 hp AC blower motor. two thermocouples (k-types) are placed in the duct i.e. one before and other after the heated plate. Thermostat setting is set at 185^0celsius. Brass plate (5 x 5 x 375 mm) is fitted in the test section without contacting the inner walls. Four thermocouples are equally placed along the length of the brass plate equidistantly. All thermocouples are of K-type with visible temperature range between -32^0celsius to $+675^0$celsius.

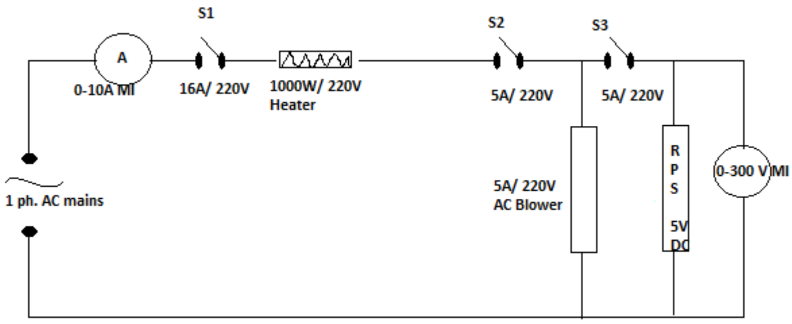


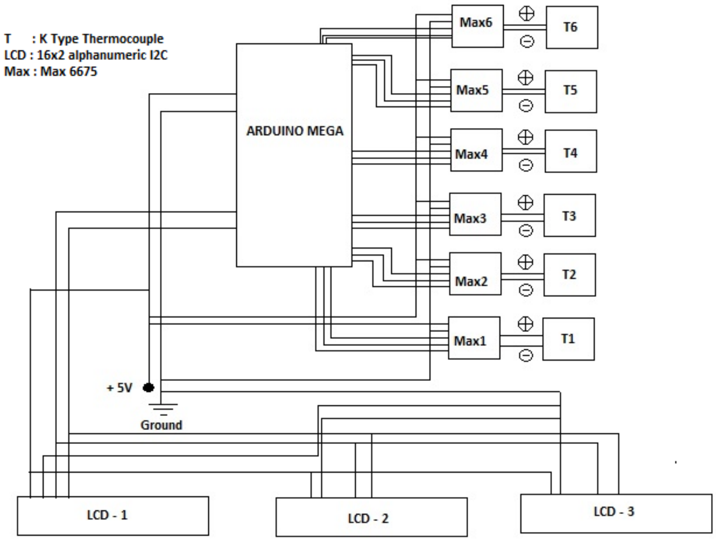


The test section represents a chimney with one flue channel without inner lining of a cylindrical pipe, vertical inner spleen pipe is considered in one stage and a helical grooved cylindrical section is considered in the other. The Helical grooved is coupled with shell and tube type heat exchanger. In this paper, only internal spleen pipe test section is considered. The central objective of the research is to determine the affects of heat transfer by reducing the chimney height and increasing the chimney draught inter alia forced circulation in the flue channels.

b. Phase Change Materials: Thin boundary layer of ferrous phosphate paste is applied along the walls of the test column. The ferrous phosphate boundary layer is responsible for increasing the effective heat transfer from cylindrical walls to outside in hot conditions. Whilst, under cold environmental conditions (operational temperature shielding can be achieved – under specific temperature zones) observed ranges are between 210 - 320^{0}c. In this paper, the inner walls are applied with thin boundary layer of Phase Change Material discussed above under three different conditions viz. (i) half boundary applied and other free surface, (ii) full boundary PCM applied and (iii) outer walls applied with PCM. The experiments revealed that, under condition (iii) mentioned above; the maximum heat transfer is achieved.

c. Electronic Sketch





d. Procedure

- **a.** Hot air is pumped into the vertical test section under buoyant conditions initially.
- **b.** The sensor data is recorded till steady state is achieved.
- **c.** Dimensionless numbers are computed under varying blower input velocity conditions i.e. 2m/s, 6 m/s, 8 m/s, .. , 20 m/s.
- **d.** Thermocouple data is recorded under varying conditions.
- **e.** For conditions under forced convection i.e. high Reynold numbers (turbulent flow); prandtl – Rayleigh numbers are computed.
- **f.** Conventional wisdom predicts that with inlet velocity of more than 6.2 m/s is turbulent and forced convection values can be achieved. For velocity ranging between 3.7 m/s- - 5.6 m/s laminar flow is observed.
- g. It is observed that at inlet velocity of 8 m/s over a length of 460 mm vertical test section; the escape velocity is 6.2 m/s.

T1	T2	T3	T4	T5	T6	Tavg.	Q in W	DT	h	Re	Pr
69.5	76	62.5	66.75	27.75	29.75	46.69	1000	29.31	1.49	23665	0.7241

67.5	62.5	60	64	33	31	47	1000	15.5	2.82	23665	0.7241
67.25	60	60	64.5	31.5	31	46.75	1000	-40.75	-1.07	23665	0.7241
66.25	62.5	60.25	65.25	32.75	32	47.56	1000	14.94	2.92	23665	0.7241
67.5	70.75	61.25	67	31.55	32	47.95	1000	22.8	1.92	23665	0.7241
67.75	70	61.5	67.75	32.5	32.75	48.63	1000	21.37	2.04	23665	0.7241
67.25	69.25	61.5	67.75	32.5	32.75	48.63	1000	20.62	2.12	23665	0.7241
66	64	60.75	66.25	35.5	33.25	48.94	1000	15.06	2.9	23665	0.7241
66	64.75	61.25	67.75	33.75	33.25	49	1000	15.75	2.77	23665	0.7228
66.25	65.25	60.75	67.5	33.75	33.25	48.81	1000	16.44	2.66	23665	0.7228

6. Conclusion

Enhancing the heat transfer characteristics of flue gases in the chimney is one of the critical deterministic features, limiting the applicability of embedding nano level circuitry onto real time technological applications. The spikes in the thermal signatures observed are detrimental to using the single flue channels whilst the cost/ benefit analysis reveals operational efficiency can be achieved with multi flue channels – single chimney. Enhancing the escape velocity of the flue gases by incorporating high end blowers, though increases the capital expenditure plays a pivotal role in reducing the corrosive gases reacting with inner lines of the chimney walls. The AL 7075 T6 alloy walls are extremely useful in enhancing conductive heat transfer through walls. While flue gases play pivotal role in convective heat transfer. The thermal signature reduction through flue gases is observed to be reduced by 18% while heat transfer through chimney walls is increased by 23.25%.

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