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Experimentally Identify the Effective Plume Chimney over a Natural Draft Chimney Model

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Abstract. The demands of energy are in increasing order due to rapid industrialization and urbanization. The researchers and scientists are working hard to improve the performance of the industry so that the energy consumption can be reduced significantly. Industries like power plant, timber processing plant, oil refinery, etc. performance mainly depend on the cooling tower chimney's performance, either natural draft or forced draft. Chimney is used to create sufficient draft, so that air can flow through it. Cold inflow or flow reversal at chimney exit is one of the main identified problems that may alter the overall plant performance. The presence Effective Plume Chimney (EPC) is an indication of cold inflow free operation of natural draft chimney. Different mathematical model equations are used to estimate the EPC height over the heat exchanger or hot surface. In this paper, it is aim to identify the EPC experimentally. In order to do that, horizontal temperature profiling is done at the exit of the chimneys of face area 0.56m², 1.00m² and 2.25m². A wire mesh screen is installed at chimneys exit to ensure cold inflow chimney operation. It is found that EPC exists in all modified chimney models and the heights of EPC varied from 1 cm to 9 cm. The mathematical models indicate that the estimated heights of EPC varied from 1 cm to 2.3 cm. Smoke test is also conducted to ensure the existence of EPC and cold inflow free option of chimney. Smoke test results confirmed the presence of EPC and cold inflow free operation of chimney. The performance of the cold inflow free chimney is increased by 50% to 90% than normal chimney.

1. Introduction

Chimneys are widely used in the industries like power plant, chemical processing plant, timber processing plant etc. to create sufficient draft. As a result, hot smoke or gases or air can escape to the atmosphere faster than the natural processes [1-3]. Two types of chimneys; natural and force draft are commonly used in the industries. In the forced draft chimney, a fan or driver is placed either at the bottom or above the tube bundle. The fan generates sufficient air flow that remove unwanted heat, smoke and dust particle from the system. In the natural draft chimney, the temperature difference between process sides and the ambient generates buoyancy force or stack effect. As a result, air flow through the chimney and remove heat waste from the system. This process is continuous until the buoyancy or stack effect is present in the chimney. There are no mechanical appliances used in the natural draft chimney. Therefore, it has more advantage than forced draft in terms of operational safety and reliability [4].

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The identified problems in the natural draft chimney that may alter its performance are cross wind, flow reversal and hot air recirculation [5]. The installation of side wall can eliminate the effects of cross wind and hot air recirculation significantly. The flow reversal or cold inflow at exit point weaken the performance of the chimney by reducing the pressure draft in chimney [6-7]. Cold inflow occurs when inappropriate chimney's height is used in the system or system draft is overcome by its depressurization [8, 9]. Very limited experimental investigations have been carried out to understand the presence, behaviour and effects of flow reversal [6-11]. Most of the related researchers measured temperature around the chimney exit or reduction air inlet temperature as a tool to determine the cold inflow. The presence of effective plume above the chimney can also be used as an indication of cold inflow free natural draft chimney. An effective plume chimney is a free boundary flow of fluid from constant heat source and it is driven by buoyancy force.

2. Effective Plume-Chimney Height (EPCH)

The effective plume chimney is formed above the hot surface due to the buoyancy force. Therefore, in the effective plume, the air velocity decreased gradually and momentum increased continuously. In the effective plume chimney, the centreline temperature remains the same as source exit air temperature. The temperature drops due to mixing and loss of buoyancy [12]. Zinoubi et al. in the year 2005, has conducted an experimental study on plume thermos-siphon interaction. In this study the horizontal and vertical temperature profile inside a cylinder is determined. The average temperature reduced along the plume vertical axis due to penetration of cold air from the side of the model. At higher level, the temperature profile is noticeably uniform which indicates the establishment of the turbulence and no penetration of cold air inflow [13]. Therefore, the Effective Plume Chimney Height (EPCH) is the extreme height of the plume chimney where centreline temperature remains the same as source exit air temperature. It would act as a solid hardware chimney but invisible in nature. Doyle and Benkly's (1973) empirical formula is the first known predictive method on the EPCH of forced and induced draft air-cooled heat exchanger.

$$h_{EPCH} = 0.8 F^{1/2} \tag{1}$$

and

$$F = 2.45 \left(\frac{\Delta T}{T_a}\right) \nu_F D_h^2 \tag{2}$$

$$v_F = 1.08 \left(\frac{\Delta T}{400}\right)^{3/8} \left(\frac{h}{6}\right)^{1/4} \left(\frac{6}{N_R}\right)^{1/2}$$
(3)

where,

 A_F = Face area of tube bundle (m²) D_h = Equivalent hydraulic diameter (m) N_R = Total tube rows number ΔT = Process side and inlet temperature difference (K) F = Ratio Buoyant force and ambient density (m⁴s⁻³)

 v_F = Velocity at inlet (ms⁻¹)

This empirical formula does not consider the significant effect of density difference. A mathematical relation is suggested by Chu in the year 2002 to estimate the EPCH for turbulence flow as follows.

$$h_0 = 10.1 \frac{L_B^{0.5} \beta^{0.8} \Delta T^{0.8} \eta^{0.3} \rho_o^{0.7}}{(\Delta \rho) g_n^{0.2}}$$
(4)

where,

 h_0 = effective plume chimney height(m)

 L_B = plate breadth (m)

 β = coefficient of thermal expansion (k⁻¹)

 η = dynamic viscosity of fluid (Ns m⁻²)

 ρ = density of fluid (kg m⁻³)

Equation (4) is a buoyancy-pressure drop balance equation solved for natural draft flow together with the heat transfer equation, yielding the airflow rate and the exit air temperature. This equation is suitable when the pressure and temperature change are linear. These mathematical formulas can be used to estimate the EPCH above the hot surface for quiescent ambient condition. [5, 14-19].

3. Experimental Procedure

Actual natural draft chimney is very large in size and shape. Therefore, it is difficult to conduct intensive research on an actual dimension natural draft chimney. In order to conduct research on natural draft chimney, different researchers used a different dimensional model that makes it difficult to compare experimental results with actual natural draft chimney. In this study, three models with chimney face areas 0.56 m², 1.00 m² and 2.25 m² with 0.3 m to 1.2 m solid chimney has been used. A wire mesh screen has been installed at the exit of the chimney. The experiments have been carried out with and without wire mesh screen for each heat load approximately 1.0kW, 1.5kW, 2.0kW and 2.5kW. An array of seven k-type thermocouples have been located above the natural draft chimney's exit to determine the centreline temperature. Five k-type thermocouples are also placed at the exit of the chimney.

4. Experimental Results and discussion

The exit air temperature has been measured for different solid chimney heights, face areas and heat loads. The temperature above the ambient value is considered as exit temperature rise. Figure 1 shows the exit air temperature rise at different heat loads. For the same heat load, it is found that wire mesh screen significantly increases the chimney's exit air temperature by reducing the penetration of cold air at exit point of the chimney. When the exit air temperature is low at a low heat load in the natural draft chimney, the cold air penetrated the chimney and mixed with hot air, resulting immediate temperature drops.



Figure 1. Exit air temperature rise for different heat load

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The temperature rise is also compared with theoretical value of temperature rise and presented in the Figure 2 and Figure 3. In Figure 2, the relations are significant for the face area of $0.56m^2$, $1.00m^2$ and $2.56m^2$ whereas in Figure 3 the relations are insignificant due to fluctuation of exit air temperature which is caused by cold inflow. The cold air is mixed with the exit air and dramatically reduces the exit air temperature. Therefore, the ratio of the calculated value and measured value fluctuate a lot. The data also indicates that wire mesh screen at the natural draft chimney model may reduce the effect of cold inflow or help cold inflow free operation of natural draft chimney.



Figure 2. Relation between calculated and actual temperature rise in natural draft chimney with wire mesh screen.



Figure 3. Relation between calculated and actual temperature rise in natural draft chimney without wire mesh screen.

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In order to identify the effective plume chimney height, it is calculated from the total pressure draft and is presented against T rise ratio in Figure 4. It is found that in the model chimney, the heights of the effective plume chimney varied from 0.14 m to 0.59 m. Since the pressure draft depends on the presence of wire mesh screen and height of the solid wall chimney as well as loss in the heating system, therefore calculated effective plume chimney heights is not accurate. Hence, heights of the effective plume chimney are also calculated from the Doyle's and Chu's empirical correlation and presented in the Figure 5.



Figure 4. Relation between measure EPCH and T raise ratio



Figure 5. Compare EPCH from different model and measured value

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The measured values have found to be significantly higher than the estimated values from Chu's empirical model but lower than Doyle's and Benkly's model. This is because estimated effective plume chimney heights from Chu's empirical model depends on bundle breadth and bundle area while Doyle's and Benkly's model equation is developed for forced draft cooling tower. It is also influenced by the face velocity. This is also supported by Chu 2006 [5]. Therefore, the effective plume chimney is investigated above the wire mesh screen with the ratio exit air temperature and solid chimney temperature at vertical axis and presented in the Figure 6, Figure 7 and Figure 8.



Figure 6. Exit temperature/ solid chimney temperature of model 0.56 m²



Figure 7. Exit temperature/ solid chimney temperature of model 1.00 m^2

The figures showed that without wire mesh at exit of the chimney, the exit air temperature is higher than the solid chimney temperature some times because the ratio is more than 1. This is only possible when cold air penetrates in the model chimney. In chimney model with wire mesh screen these ratio

are always below the unit value that indicate exit air temperature is higher than solid chimney temperature. That is an indication of cold inflow free operation of chimney model.



Figure 8. Exit temperature/ solid chimney temperature of model 2.56 m²

According to the definition of effective plume chimney after the chimney exit the temperature in vertical direction is constant. The temperature is constant until the effective plume present above the chimney exit. Figure 9 and Figure 10 show the vertical temperature profile above the solid wall temperature.



Figure 9. Vertical temperature profile above the solid wall chimney without wire mesh screen

In Figure 9, it is found that in 0.03 m height, the temperature values fluctuate from 45° C to 52° C. It indicates the absence of plume chimney above the solid wall chimney where there is no wire mesh. In Figure 10, the temperatures are fluctuating at side but it is found to be almost linear at middle. The

side thermocouples are disturbed by the surrounding air whereas plume is existing at the middle. It also found that wire mesh significantly protects the penetration of cold inflow.



Figure 10. Vertical temperature profile above the solid wall chimney with wire mesh screen

5. Conclusion

The natural draft chimney performance is highly influenced by the flow reversal problems. The exit dimension, temperature distribution and draft loss in the natural draft chimney are responsible for the presence of cold inflow. The wire mesh screen significantly eliminates the cold air penetration problem and helps to establish an effective plume chimney about the solid wall chimney. Experimental results show that effective plume chimney exists in the natural draft chimney when it operates without the effects of cold inflow. The mathematical correlations could be used to state the presence of effective plume chimney but results have found significant error when compared with experimental values.

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