

Using a Split Chimney for Dilution of Exhaust Pollution: A CFD Approach

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Abstract. There is a demand to lower the concentration of toxic gases and smoke in the vicinity of the chimneys at low wind speed. This article deals with the advantages of using a novel and low-cost configuration which has already successfully been used to generate fire-whirls in the laboratory. The computational results show that the configuration named split chimney is able to generate a swirling flow when a hot air flow is used instead of a fire. In addition, the results show that the split chimney is able to lower the concentration of harmful gases at the outlet of the chimney without significant adverse effect on the plume rise.

Keywords: chimney, split chimney, pollution, dilution, concentration.

1. Introduction

The poor air quality in urban areas is mainly due to the increasing population, leading to industrial activities. World population has doubled in forty years from 1959 to 1999. In addition, there has been a 4% increase of people living in urban areas with respect to total population. The main urban source of air pollution is the combustion (Fenger, 1999). Chimney exhausts such as sulphur dioxide, nitrogen dioxide, carbon monoxide, soot, and volatile organic compounds are the main source of air pollution. They have serious impacts on human health and affect the lung and the respiratory system. They also may deposit on soil, plants, and in the water, further contributing to human exposure. The World Health Organization (WHO) reports that 1.3 million lives who reside in the middle-income countries are likely lost by urban air pollution around the world per year (WHO, 2011).

In addition to classical methods which deal with the smoke before exhausting to the atmosphere; the dispersion of smoky plume by local winds is considered as integrated way to meet air pollution rules and regulations in the vicinity of the chimneys. Air pollution laws generally require that large combustion sources such as power plants are equipped with scrubbers or other devices in order to reduce the amount of smoke entering the atmosphere ("Smoke," 2011). However, further dispersion of smoky plume is still required in order to avoid the accumulation of harmful chemical species into the stagnant atmosphere above the urban areas (N. Kozarev & Ilieva, 2011). In addition to overall pollution, the concentration of toxic gases around the chimney is a major concern. For example, McCormick reports that, in the near downwind vicinity of a moderate local source of SO_2 , observed short-term concentrations of gas at ground level may reach $3000 \mu\text{g}/\text{m}^3$ when the overall urban average is on the order of $300 \mu\text{g}/\text{m}^3$, and concentration in the clean air entering the city is on the order of $30 \mu\text{g}/\text{m}^3$ (McCormick & Scorer, 1971). Three effective ways to decrease the concentration of pollutant in the ambient air are; using tall chimneys, increasing the plume rise, and reducing the emission rates (FPA, 2010).

This research investigates a potential application of a new configuration to reduce the air pollution around a chimney. The proposed low-cost configuration is inspired from a similar configuration which is

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commonly used to generate fire-whirls and it can be used in conjunction with previous techniques to reduce the exhaust pollutions. Previous research indicates a split channel is able to generate a stable fire-whirl; increase the burning rate of fuels placed at the base of the chamber, and elongates the height of the fire (Chuah, Kuwana, & Saito, 2009; M. I. Hassan, Helali, & Saito, 2001; M.I. Hassan, K., K., & F., 2005; Kuwana, Morishita, Dobashi, Chuah, & Saito, 2011). However, there is no previous research indicating such configuration can generate a swirling flow if a hot rising air flow is used instead of fire. This research investigates the possibility of generating a swirling flow within the split chimney when hot air representing toxic gases and smoke enters from the base of the configuration. The dilution of the toxic gas at the top of the configuration is also investigated. The effect of the configuration on the plume rise is also investigated.

In the absence of any previous computational and experimental results, a chimney has also been modelled in order to assess the accuracy of the modelling. There are sufficient previous works on the plume rise of a chimney. Briggs (G.A. Briggs, 1969b, 1971; G.A. Briggs, 1972) presented the plume rise formulation. The plume rise equations are based on the assumption that plume rise depends on the inverse of the mean wind speed and is directly proportional to the two-thirds power of the downwind distance from the source. Different equations are used for different atmospheric stabilities. Pasquill stability classes are categories which used to measure the quantity of turbulence in the ambient air. The plume rise and the plume dispersion have significantly been affected by turbulent quantity. The group A of the stability classes means that the ambient air is very unstable where the ambient temperature gradient is less than -0.01895 K/m (Beychok, 2005). For the Pasquill stability class A (unstable conditions), Briggs states that the maximum height of plume can be found at ten stack heights downwind where after this point, the plume stop rising. He used buoyancy parameter (F), which is defined as follows(Beychok, 2005);

$$F = gV_s r^2 (T_s - T_a) / T_s \quad (1)$$

Where F is buoyancy parameter (m^4/s^3), g is gravity (m/s^2), r is internal radius of stack (m), T_a is ambient air temperature (K), T_s is stack gas temperature (K) and V_s is stack exit velocity (m/s). The plume rise in the case of buoyancy parameter (F) less than 50 for an unstable condition can be estimated using the following formulas (G. A. Briggs, 1969; G.A. Briggs, 1969a),

$$\Delta h = 1.6(F)^{1/3}(X)^{2/3}(u)^{-1} \quad X < 10 h_s \quad (2)$$

$$\Delta h_{\max} = 1.6(F)^{1/3}(10 h)^{2/3}(u)^{-1} \quad X > 10 h_s \quad (3)$$

$$\Delta h = H_e - h_s \quad (4)$$

The equation 2 can be used to estimate the plume rise for the rising stage of the plume and equation 3 to estimate the maximum height. X represent downwind distance from the centre of the stack (m), h_s is actual stack height (m), u is wind speed (m/s), h is height in the vertical direction (m), Δh is rise plume (m), H_e is emission height (m), Δh_{\max} is maximum plume rise (m).

2. Methodology

A standard chimney and a split chimney are modelled using a commercial CFD package (ANSYS-CFX).The computational domain is identical for both cases and is shown in Figure 1a. The domain has a rectangular base $20 \text{ m} \times 22 \text{ m}$ and its height is 15 m . The domain includes air as the ideal gas with the temperature of 25°C and the pressure of 101325 Pa at the base. The initial turbulent intensity in the domain is assumed to be 5% . The hydrostatic pressure change is included using the following equation(Pozrikidis, 2009);

$$p = p_0 \exp(-gy/RT) \quad (5)$$

Where p represents opening pressure (Pa), p_0 is reference pressure (101325 Pa), y is height with respect to the reference point (m), R is air constant (287.1 J/kg/K) and T is reference temperature (298.15K).

The wind with uniform speed of 0.5 m/s and a static temperature of 25°C blows in z direction and enters the domain from the left side (see Fig.1c). The gravity is in the negative y direction and the intensity of the turbulence is assumed to be 5% .

Two configurations are located at 2 m from the left side at the base of the domain. The standard chimney has an internal diameter of 0.25 m , a height of 2 m , and the wall thickness of 0.02 m (Fig. 1b). The split

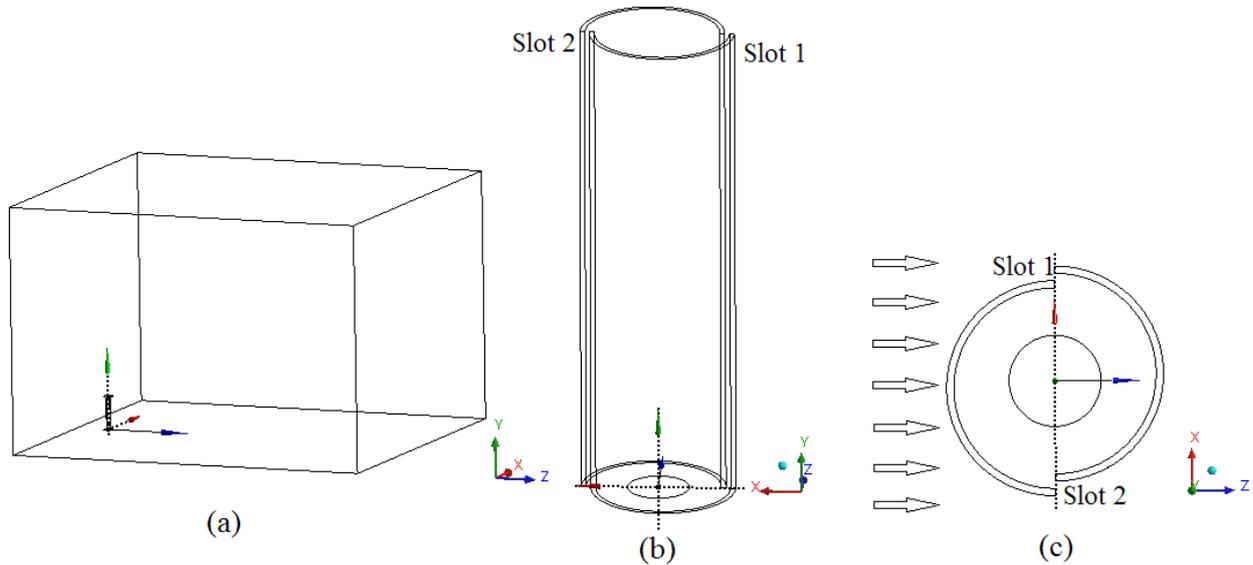


Fig. 1: Geometries of the split chimney and the domain. (a) location of the split chimney within the domain; (b) left view of the split chimney; (c) top view of split chimney.

chimney with two gaps has an internal diameter of 0.55 m, a height of 2 m, the each gap of 0.02 m, and the wall thickness of 0.02 m (Figs. 1b & 1c). In the case of the split chimney, two half cylinders are located 0.05 off centre at the x-direction (Fig. 1c). The middle point of the centres of the two half cylinders coincides with the centre of the inlet where the hot air enters the configuration from a circular inlet with the diameter of 0.25m at the base of the configuration (see Fig. 1b). The static temperature and total pressure of the inlet flow into the configurations is at the temperature of 100°C and total relative pressure of 0 Pa. In addition, the turbulent intensity of the plume is assumed to be negligible. The plume compositions depend on the condition of the combustion and the type of the fuel. For simplicity, the plume has been assumed to have the air properties and is treated as an ideal gas with constant thermal properties.

The chimney's walls and the domain bottom side are considered as adiabatic walls and the flow does not slip respect to them. The other sides of the domain except the left side are assumed to be “opening boundary”. The opening boundary condition is very convenient when the velocity direction is not known but the pressure values are known. The hydrostatic pressure changes are also applied to all sides and the top of the domain using equation 5. The solver treats the specified pressure as total pressure for inwards flow and as hydrostatic pressure for outward flows. The air temperature at all openings equals 25°C.

The governing equations are the continuity, the Navier–Stokes equations, and thermal energy equation. Thermal radiation is not modelled for the steady state model. The Reynolds Stress turbulent model (Speziale, Sarkar and Gatski model (SSG)) is selected. The SSG model offers good predictions of swirling and buoyancy flows(ANSYS, 2010). Bergstrom recommended the Reynolds stress model for more realistic simulation of a strong streamline curvature which is expected at the top of the configurations in this work(Bergström, 1997).

A combination of tetrahedral and wedge elements are selected for meshing. In the case of the standard chimney, the number of tetrahedral elements is 331,578 and the number of wedges elements is 19,851. For the split chimney, these numbers are 663,047 and 239,140, respectively. The accuracy of the simulation is checked by running two simulations. In the first simulation, the domain size increased by 20%. In the second simulation, the number of meshes increased by 20%. The results show the presented results are independent of the domain size and the number of the elements.

3. Results

3.1. Swirling flow within the split chimney

The first research question is whether the split chimney is capable of generating the swirling flow within the chamber if an inlet hot air is used instead of a fire at the base of the configuration. To visualize the swirling, the velocity vectors within the split chimney at three heights (y) of $y/d=0.001$ (base of the chamber),

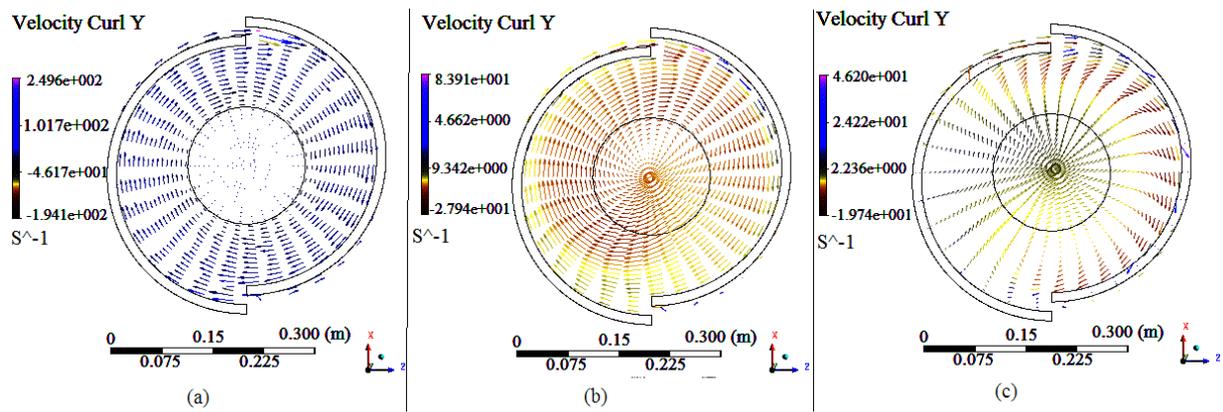


Fig. 2: Top view of velocity vectors at different height of the split chimney. (a) $y/d=0.001$; (b) $y/d=1.82$; (c) $y/d=3.64$. $y/d=1.82$ (mid-height of the chamber), and $y/d=3.64$ (top of the chamber) are plotted in Figure 2 where d represents the diameter of the split chimney. Figure 2a indicates the velocity vector coloured by curl at the height of $y/d=0.001$. The maximum curls at y direction (249.6 s^{-1}) occur at slot 1 which faces the wind. The swirling is also intense at slot 2 which is opposed to the wind direction. There are swirling flows around the rising plume but they do not influence the plume. At the mid-height of the chamber (see Fig.2b), the maximum velocity curl at y direction is 83.9 s^{-1} and occurs at slot 1. The rising plume completely rotates and the minimum curl at y direction is 5.8 s^{-1} . At the top of the chimney (see Fig. 2c), the wind affects velocity vectors. The wind boosts the velocity at slot 1 (see Fig. 2c) where the velocity vectors are in the direction of the wind and weaken the velocity at slot 2 where the velocity vectors oppose the wind.

3.2. Dilution

The main potential advantage for the split chimney is its ability to lower the concentration of the toxic gases emitted from a chimney. Figure 3 shows the streamlines originated from the inlet (black colour) and the sides' intakes (grey colour). It shows that the discharge of the chimney at the top is a mixture of the inlet hot air containing toxic gases and smoke, and fresh air entered from the side slots. The hot air flow rate from the based inlet and fresh air flow rate from slots 1 & 2 are calculated to be 0.1 kg/s , 0.07 kg/s and 0.03 kg/s , respectively. This indicates that the outlet contain 50% of fresh air which will halve the outlet concentration of the smoke and toxic gases.

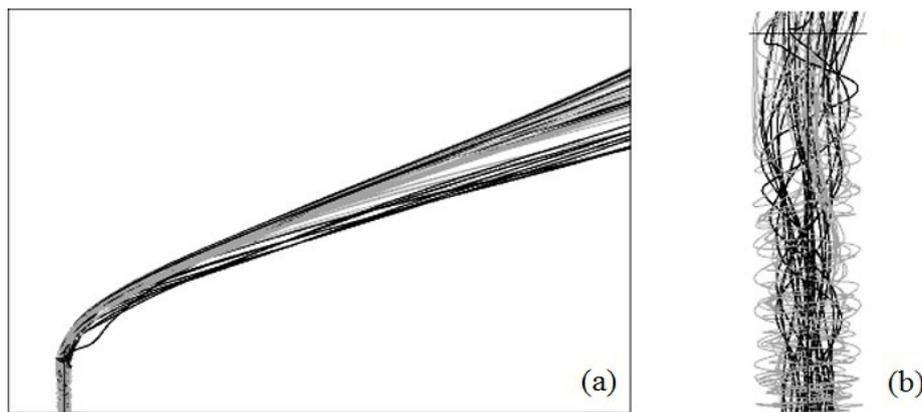


Fig. 3: The behaviour of the hot air flow inside and outside split chimney : (a) The overall path of the hot air (black streamlines) and fresh air intake (grey streamlines) from the split chimney; (b) the flow of fresh air within the split

3.3. The boundaries of Plume

Figure 4a indicates the results for the upper and lower boundaries of the plume and its path after emitting from the chimney. The plume centreline is plotted and is compared with the results from Brigg's formula. First from equation 1, the buoyancy parameter (F) is calculated to be $0.09 \text{ m}^4/\text{s}^3$ assuming $g=9.81 \text{ m/s}^2$, $V_s=3.12 \text{ m/s}$, $r=0.125 \text{ m}$, $T_s=372.92 \text{ K}$, and $T_a=298.15 \text{ K}$. The plume centreline then is plotted using equations

2 and 4. The results show that the results of the computational modelling and the equation 2 are in a good agreement in the vicinity of the chimney. The maximum error of 7.2% occurs at $z=0.642$ m. However at further distances from the chimney, the error reduces to 4.6 % at $z= 5.8$ m or at the end of the rising region. As the distance from the chimney increases, deviation between the CFD results and the Briggs's equation (equation 3) increases and reaches to a maximum of 14% at $z=19$ m.

Figure 4b compares the boundaries of the plume emitted from the standard chimney and the split chimney. According to the results, the boundary of the plume for the split chimney is always less than that for the standard chimney and the difference increases as the distance from the source increases. The maximum difference is at $z=19$ m where the maximum plume rise for the standard chimney and the split chimney is 15 m and 12.6 m, respectively. It should be noted that the average temperature of the exhausts at the top of the standard chimney is 99.77°C which is greater than that for the split chimney 62.83°C .

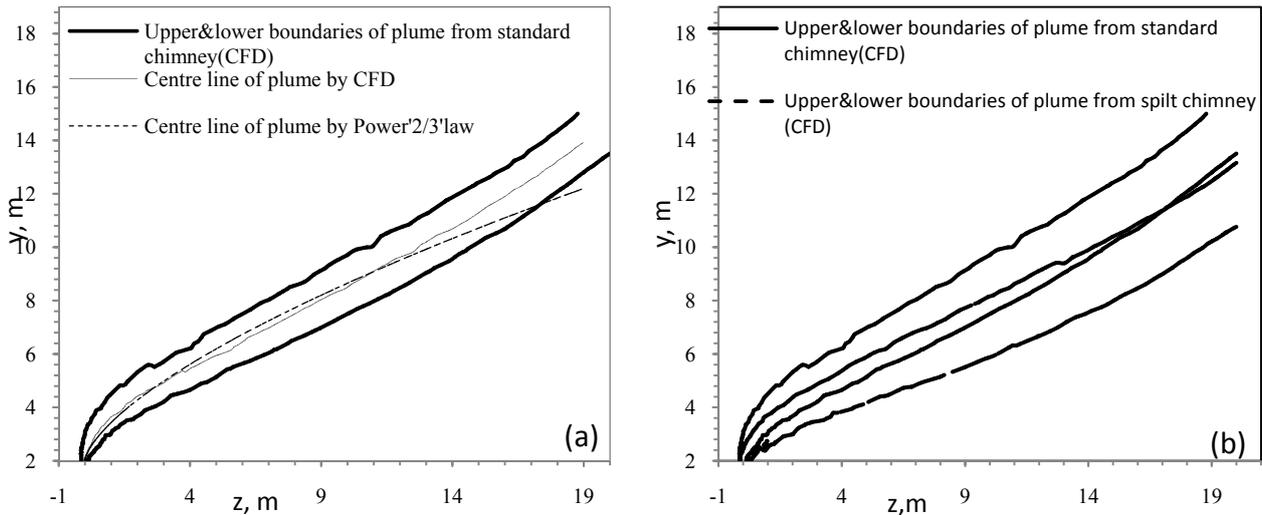


Fig.4: The boundaries of plume from chimneys and the centreline of plume from standard chimney (a)Comparing the centreline of plume from standard chimney estimated by CFD modelling and that by Briggs's formula, (b)Comparing the plume path of the chimney and the split chimney obtained from CFD modelling

4. Discussion

The results show that the split chimney is capable of producing a swirling flow within the configuration. At the lower heights of the chimney, the maximum swirling occurs at slot 1 but it does not influence the plume except at the perimeter. At the mid-height of the split chimney, the maximum swirling occurs at slot 1 but its value is less than that at the base. This indicates that the suction is reduced which decreases the velocity of air at slot 1. The plume is fully influenced by the swirling induced by the side intakes. At the top of the chimney, the velocity curl at slot 1 is decreased respect to that at the mid-height of the chamber. This is expected as the chamber has a limited capacity and loses its suction at higher heights. The plume is affected by wind and loses its circulation.

The split chimney mixes the fresh air from the side intakes into the plume and results in a lower concentration of the toxic gases at the top of the split chimney. The modelled chimney geometries were somewhat arbitrary and were not optimized for mixing but it is still able to lower the concentration of toxic gases by about 50%.

The plume rise from the modelled standard chimney is in a good agreement with that estimated from Brigg's equations but the deviation increases as the distance from the chimney increases. The thermal radiation is not modelled and this can explain the deviation. In practice, the exhausts of the chimney become cooler due to mixing with ambient air, conduction, convection, and thermal radiation.

The plume rise from the split chimney is less than that for the standard chimney as the buoyancy reduces with the reduction in air temperature. This was expected as temperature at the top of the split chimney

(62.83°C) is less than that for the standard chimney (99.77°C) due to mixing of the fresh air and the plume within the chamber. The reductions of outlet temperature can assist to prevent some of the chemical reactions continuing within the plume.

5. Conclusion

A split chimney with arbitrary geometries has been modelled to assess its ability to generate swirling flow within the chimney, and its ability to lower exhaust smoke and toxic gases. The results indicate that the low-cost configuration is capable of generating the swirling flow and halving the concentration of the exhaust toxic gases and smoke. However, the plume rise is moderately reduced.

6. Acknowledgements

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