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The effect of wind speed on the performance of a split chimney

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Abstract. In densely populated areas, smoke and toxic gases from chimneys are a matter of concern. The concentration of the toxic gases should be lowered before reaching ground level. It has being conceived a simple configuration including two half cylinders is potential to reduce the concentration of the toxic gases within the chimney. The split chimney is modeled and its performance under a wide range of wind speeds is evaluated. The results indicate that the split chimney does not have an ad verse affect on the discharge o f the chimney and is able to reduce the concentration of the exhaust toxic gases at all wind speeds. The results also show there is a side leakage as wind speed increases. Further studies are needed to improve the performance of the split chimney.

Keywords: split chimney, wind speed, dilution, leakage

1. Introduction

One of the negative effects of the industrial revolution is dust, smoke, and toxic gases ejected from chimneys. The exact composition and characteristics of combustion gases, and the severity of their effects depend on the type of fuel being burned and the condition of the combustion. Some toxic and harmful products are carbon monoxide, sulphur dioxide, nitrogen oxides and particulates. The poisonous gases and smoke discharged from chimneys may defoliate the surrounding environment kilometres away from the chimney (Amasa et al., 1975). They represent a health hazard and cause health issues, such as chronic eye inflammation and lung damages. The concentration of the toxic gases should be reduced before reaching the surface. Most governments imposed strict regulations and tax systems to limit the pollution discharged from chimneys. The pollution should be treated and to be lowered to a certain value. However, the discharges still contain toxic gases, even after the best treatment (Bosanquet et al., 1950). The use of tall chimneys reduces the local pollution. Wind dilutes the discharges of the chimney before reaching the ground; however, during dilution some heavier harmful gases descend (Bosanquet et al., 1950). The downwind concentration of air pollutants emitted from a chimney depends on many variables such as wind speed and direction, atmospheric turbulence, ambient air temperature, ambient temperature inversion, chimney height and diameter, exit velocity, exit temperature, exit mass flow rate, terrain elevations, height and width of any obstructions in the vicinity of the chimney (B. and R., 2000). The worst scenario in terms of toxic and dust concentration near chimneys occurs when there is a temperature inversion or low ambient wind speed (APTI, 2010, Wee and Park, 2009).

Several configurations are currently used to generate fire whirl, including a simple cylindrical chamber with some side openings. The air enters the chamber tangentially and causes the fire to rotate. The resulting swirling flow increases the burning rate and elongates the fire (Snegirev et al., 2004, Chow et al., 2011). The entrained flow provides the extra oxygen required for a faster burning rate. It is possible that such configurations could prove to be useful to dilute the toxic gases within the chimney before discharging them into the environment, causing less pollution in the vicinity of the chimney. A recent study (Al Atresh et al.,

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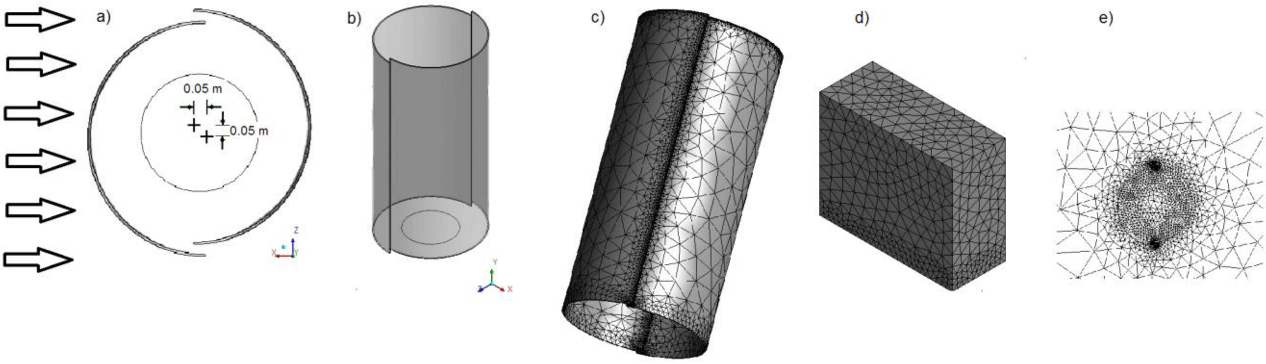


Figure 1: Details of the model and mesh, a) top view of the split chimney, b) side view of the split chimney, c) surface mesh around the split chimney, d) the domain meshes, and e) the surface mesh around the hot air inlet.

2012) shows that a split chimney which substitutes raising hot air instead of the fire is capable of generating swirling flow and diluting the outlet concentration.

The results also indicate that the chimney does not significantly reduce plume rise under very low speed wind (0.5 m/s). However, it is necessary to assess the performance of such low-cost configuration under medium and high wind speeds in terms of discharge mass flow rate, dilution of harmful gases, and possible leakages from the side openings.

2. Modeling

Three configurations are modelled using commercial CFD software, ANSYS-CFX. The first configuration represents a simple chimney with an external diameter of 0.5m, height of 2m and wall thickness of 0.01m. The second configuration, or the split chimney, consists of two identical half cylinders which are cut from a pipe along its central axis. The pipe has a height of 2 m, external diameter of 1 m and wall thickness of 0.01 m. The two half hollow cylinders are placed 0.071m off centre, 0.05m in each horizontal direction (see Fig. 1a). The circular hot air/smoke entrance has a diameter of 0.5m and its centre coincides with the middle point of the line joining the centres of the two half cylinders (see Figs.1a & 1b). The third configuration, or the wide chimney, is a cylindrical chimney with a height of 2m, diameter of 1m and wall thickness of 0.01 m and its centre coincides with the centre of the hot air inlet. The geometry of the inlet is identical to the previous configuration. The first and the third configurations are modelled to provide reference values to assess the performance of the split chimney under different wind speed conditions. The three dimensional rectangular domain has a height of 20m and extends horizontally 5m to the left and 20m to the right side of the configuration. The wind enters the domain from the left side (see Fig 1a). In the case of zero wind speed, a large domain (30m ×30m with a height of 50m) is modelled and the configurations are placed in the centre of the base.

The number of computational elements that is necessary for a converged result varies among configurations and depends on the wind speed. For the split chimney, 304024 tetrahedral elements are used. Their sizes vary from 5 mm around the chimney to 2000 mm near the side walls. Figure 1c shows the surface mesh around the split chimney and Fig. 1d shows the domain meshes. The bottom view of the surface elements around the smoke inlet is shown in Fig. 1e. In the case of zero wind speed, 481729 tetrahedral meshes are used. For the wide chimney, 90120 tetrahedral elements are used and their sizes vary from 5 mm to 2000 mm. The number of meshes increases to 146628 in the case of zero wind speed. For the chimney, 63796 tetrahedral elements are used but this number increases to 121503 when wind speed is zero.

2.1. Governing equations

The governing equations are continuity, thermal energy, and Navier-Stokes equations. The Boussinesq approximation which is commonly used in buoyancy driven flows is not used, as the temperature difference between the inlet hot air (100^{o} C) and the ambient air (25^{o} C) is not small. The thermal energy equation which is an alternative form of the energy equation is used as it is suitable for low-speed flows. The flow, particularly within the chimney, is expected to be turbulent. Previous studies on fire-whirls demonstrate that the k-ε model gives good agreement with experimental results (Snegirev et al., 2004). However, a modified version of the model (ReNormalization Group or RNG) is used instead of the standard model. The model is developed based on the Navier-Stokes equations, similar to the standard k-ε model, but the constants differ. Ref.(ANSYS, 2009) reports that the RNG model improves the results compared to the standard model.

2.2. Initial and boundary conditions

In practice, the composition of combustion gases varies for different fuels and includes a wide range of products. In this work, the products are assumed to have the properties of air. The air is assumed to be an ideal gas and compressible and the thermodynamic properties of the air varies with temperature.

The walls had no slip boundary conditions which were assumed to be smooth and adiabatic. Thermal radiation is not modelled. The ambient temperature is assumed to be constant (25^{o}C) but hydrostatic pressure changes are included.

The top, right, front and back sides of the computation domain are set as "opening" boundary condition. The opening boundary condition is convenient when the pressure is known but the velocity direction is unknown. The specified pressure is taken to be static pressure if the flow is directed out of the domain but if the flow is entering the domain, the specified pressure is treated as total pressure.

The left side of the domain is treated as inlet boundary condition. The wind speed is specified in each case and the static temperature is defined as 25^{o}C. The hydrostatic pressure is applied using eq.1(Pozrikidis, 2009). The hot air inlet at the bottom of the chimney is also defined as inlet but treated differently. Instead of specifying the velocity, the total relative pressure and temperature are specified and taken as 0 Pa and 100^{o}C, respectively. During the solution, the solver adjusts the specified pressure to match downstream conditions.

$$p = p_0 \exp\left(-gy/RT\right) \qquad (1)$$

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).

2.3. Accuracy

The simulation is initially run using the first order and then the high resolution scheme. The convergence criteria for all variables (velocity components, mass, energy, k and ε) are set to 1×10^{-5} based on RMS residuals. Two methods are used to assure the robustness of the results. In the first method, the number of the elements is increased by 20% and the results are compared with the original results. In the second technique, the domain sizes are increased by 20% in all directions. The checks are carried out for all configurations at wind speed of 5 m/s. The results indicated insignificant changes in velocity distribution.

Several simulations are carried out using standard k-ε, Reynolds stress, k-ε and laminar models in order to test the sensitivity of the results with respect to the model selection. The results indicates that the maximum velocity at the top of the configuration changes less than 2% except for the laminar model which indicated changes up to 5%.

3. Results

3.1. Discharge capacity

The foremost concern regarding a chimney is its ability to transfer flue gases using stack effect. The discharges of all configurations in a wide range of wind speeds are computed and plotted in Fig.2. According to the results at zero wind speed, the discharge of the split chimney is 0.573 kg/s which is lower than the discharge of the wide chimney (0.654 kg/s) but is greater than that of the chimney (0.556 kg/s). The wide chimney is expected to have a higher discharge than the chimney due to its larger diameter. The split chimney carries a lower discharge than the wide chimney because of the mixing of the inlet fresh air from the sides with the inlet hot air from the bottom of the base lowers the average temperature. The average temperature at the top of the split chimney is 356.13 K. The difference between this temperature (356.13 K) and ambient temperature (298.15 K) represents the buoyancy. The change of the temperature along the height of the enclosure is negligible for other two configurations. It should be noted that the induced swirling compensates the loss of the buoyancy to some degree. The average induced velocity curl at the top of the chimney and in the negative direction of the y axis is computed to be 13.5 s-1 (see Fig.1b).

As the wind speed increases, the discharge of all configurations increases but the rate of the increase for the chimney is rather small compared to other two configurations. The discharge of the wide chimney remains slightly higher than that of the split chimney until the wind speed reaches 10 m/s. At this wind speed, the discharge of the wide chimney, the split chimney and the chimney is computed to be 1.49 kg/s, 1.48 kg/s and 0.75 kg/s, respectively. The average temperature and velocity curl in the negative direction of the y axis at the top of the split chimney reach values of 328.8 K and 18.9 s^{-1}, respectively. In the cases of the chimney and the wide chimney, the average temperature at the top of the enclosures remains largely unchanged. This is expected as radiation and heat transfer from the configuration walls are not modelled.

At wind speeds greater than 10 m/s, the discharge of the split chimney becomes slightly greater than that for the wide chimney. For example, at a wind speed of 50 m/s, the discharge becomes 6.93 kg/s, 6.84 kg/s and 3.31 kg/s for the split chimney, the wide chimney and the chimney, respectively. The average temperature and curl in the negative direction of the y axis at the top of the split chimney become 356.5K and 43.5s^{-1}, respectively.

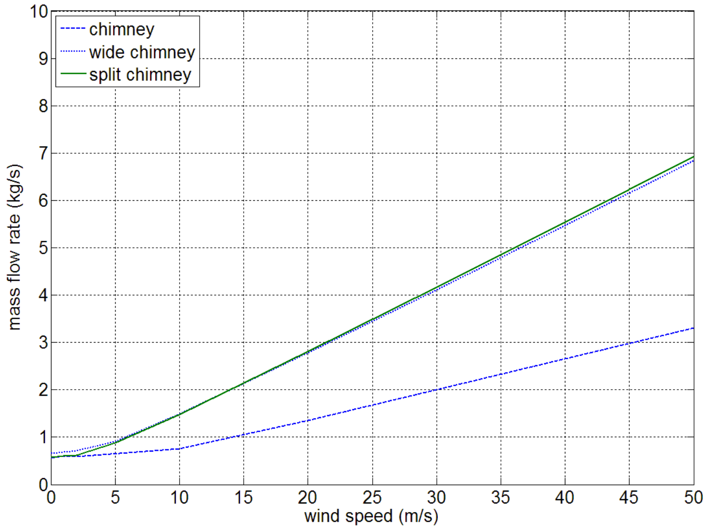


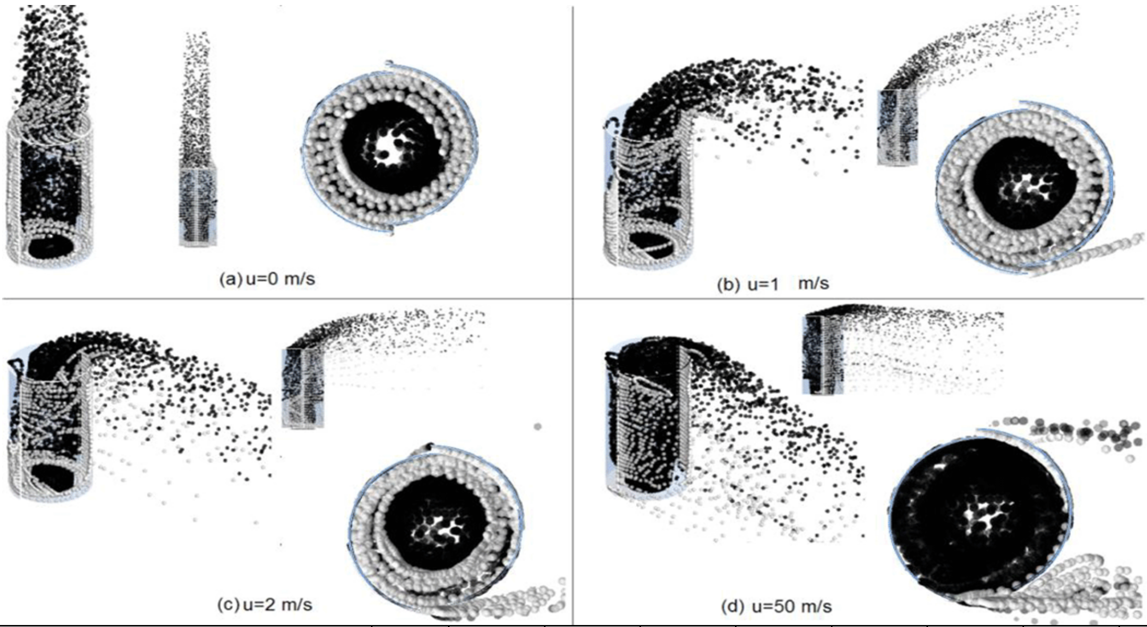
Figure 2: Discharge mass flow rate at the top of the chimney, the wide chimney and the split chimney

3.2. Dilution

The main objective of present work is the dilution of the toxic gases and smoke within the split chimney. The mass flow rate of the smoke and inlet/outlet air from sides A and B (see Fig.1a) at various wind speeds are presented in Table 1. The second row shows the mass flow rate of the inlet toxic gases/smoke in kilograms per second. The remaining rows of table 1 indicate normalized values with respect to the first row. The mass flow rate of the inlet air from sides A and B are equal at the wind speed of zero and no air exits from these sides. Total intake air flow from both sides is equal to 38% of the toxic gas/smoke mass flow rate or a 28% dilution of the smoke (1-1/1.38). At wind speed of 1 m/s, the percentage of the intake from side A drops to 6.6% and some of the air within the split chimney exits this side (2.7%). It should be added that no smoke is detected to exit this side at this wind speed. The inlet air from side B increases to 25.7% for this wind speed. The total entrained air is 29.6% which equals to 22.9% of the smoke dilution at the top of the chamber. At velocity of 2 m/s, the inlet and outlet mass flow rates become equal at side A. The air enters the chimney from the lower sections of the side A and air within the chimney leaves at the higher sections of this side. It is observed that the outlet contains a very low percentage of the smoke. Further increase of the wind speed reduces the air intake from side A and it reaches a minimum of 0.5% at the highest wind speed (50 m/s). The leak from side A rises by increase in wind speed and reaches a value of 20.8% at wind speed of 50 m/s. The intake air from side B increases to 46% of the bottom inlet at wind speed of 40 m/s. The mass flow rate of the intake air from side B continue to increase with further increase of the wind speed but the percentage with respect to the mass flow rate of the hot air inlet remains unchanged. No leak has been detected from side B at any wind speed. The concentration of the toxic gases/smoke at the top of the split chimney reaches 81% at wind speed of 5 m/s and meets a constant value of 80% at wind speeds greater than 10 m/s.

Table 1: Intakes and discharges from the top and the sides of the split chimney at different wind speed

Wind speed (m/s)	0	1	2	5	10	20	30	40	50
Inlet plume mass flow rate (kg/s)	0.573	0.604	0.617	0.876	1.476	2.806	4.166	5.538	6.931
Inlet fresh air from side A/inlet plume (%)	19	6.6	5	0.8	0.5	0.5	0.5	0.5	0.5



Leak from side A/inlet plume (%)	0	2.7	5	14.9	19.2	20.6	20.8	20.8	20.8
Inlet fresh air from side B/ inlet plume (%)	19	25.7	28.2	37.4	43.1	45.3	45.8	46	46
Total inlet fresh air from sides/ inlet plume (%)	38	29.6	28.2	23.2	24.3	25.2	25.5	25.6	25.7
Plume concentration at the top (%)	72	77	78	81	80	80	80	80	80

Figure 3: Side view, front view and top view of the distribution of the inlet hot air (black balls) and side fresh air intakes (white balls) at four different wind speeds, a) zero wind speed, b) wind speed of 1 m/s, c) wind speed of 2 m/s, d) wind speed

Further investigation is carried out to identify the quality of the mixing. Figure 3 shows the streamlines originated from the bottom inlet (indicated by black balls) and the air streamlines that pass two side openings (indicated by white balls). The domain was clipped at the height of 2 m for the top view. Figure 3a shows in a still ambient, no air escapes from the sides and the hot inlet air swirls within the chamber and intends to mix with the surrounding entrained air due to the centrifugal force. The mixing is done relatively well except at the centre of the smoke. By increasing the wind speed to 1 m/s, the mass flow rate of the inlet hot air and the fresh air intake from side B increases. This reduces the size of the core of the vortex (Fig. 3b). As the split chimney has a definite volume, the intake from side A decreases which results a lower total intake from the sides. Some fresh air also leak from side A but they do not contain any toxic gases or smoke (see Fig. 3b). The leakage occurs over the height of 1.22 m. At wind speed of 2 m/s, some smoke leak from side A. The fresh air leakage occurs over the height of 0.98 m but the smoke leaks over height of 1.42 m. The distribution of the smoke and fresh air remains unchanged. By a further increase in wind speed, the smoke mass flow rate increases and penetrates through to the outside which results in reduction of the thickness of the peripheral layer of fresh air. It is observed that the most fresh air intakes from the sides remain at the opposite side of the chamber to the wind. However, some fresh air exists at the wind side of the split chimney in the lower height of the chamber. At the highest wind speed (50 m/s) (see Fig. 3d), the thickness of the fresh air layer reduces. The fresh air and smoke mix only on the opposite side to the wind. The minimum height that smoke leaks from side A reduces to 0.72 m. It should be added that smoke leakage is negligible in all wind speed cases. The mass flow rate of the smoke leaving side A with respect to the inlet hot mass flow rate reached to a maximum of 1.7% at the wind speed of 50 m/s. This value corresponds to the smoke concentration of 8% ($1.7/20 \times 100$). There is no air or smoke coming out of side B at any wind speed. However, Fig. 3c & 3d show that some smokes coming out from the top of the configuration descend particularly at high wind speed.

4. Discussion

As hot air and smokes rise in a split chimney, it mixes with fresh air and loses buoyancy but its discharge capability does not decrease due to the swirling effect. The average temperature at the top of the split chimney is lower than the average temperature of the wide chimney at all wind speeds. Previous research on fire whirls induced by split chimneys show that the burning rate and the height of a fire increase as the swirling intensifies. In the case of hot air, the expected significant increase of the discharge due to swirling does not occur. The observed increase is due to a larger diameter channel and this can be proven by comparing the results of the wide chimney and the split chimney. This is mainly because there is no fuel at the base of the chamber to interact with the swirling flow.

The split chimney is able to reduce the exhaust smoke and toxic gas concentrations at all wind speeds. The best performance is achieved at zero wind speed. In that case, the concentrations of smoke and toxic gases at the outlet of the split chimney reduced by 28%. The split chimney becomes slightly less effective at higher wind speeds. It dilutes the exhaust toxic gases and smokes by 20% at wind speeds greater than 5 m/s. It should be noted that effectiveness of the split chimney at high wind speeds is less significant due to a rapid dilution of the exhausts with air in its vicinity. The degree of the dilution from the split chimney is not sufficient for most practical applications. However, the 20%-28% dilution could be achieved using a low-cost and low-maintenance configuration.

The investigated split chimney could not homogenously mix the fresh air intakes from the sides and the inlet smoke and toxic gases from the bottom of the domain particularly at high wind speeds. At low wind speeds, the fresh air surrounds the smoke but does not significantly permeate. This is not necessarily a drawback as the layer of the fresh air around the smoke is expected to delay its dilution in the vicinity of the chimney. At higher wind speed, the layer of the fresh air only covers the exhausts on the opposite side to the wind. This is not essentially a disadvantage as this side is expected to descend first on the surrounding areas.

The main drawback of the simulated split chimney is the side leakage occurring at wind speeds greater than 2 m/s. As the wind speed increases, the side leakage appears at the lower height of the chimney. However, the smoke concentration of the side leak is relatively small and reaches to a maximum of 8% at the highest wind speed (50 m/s).

5. Conclusion

The performance of a split chimney commonly used to induce fire-whirl at a wide range of wind speed (0-50 m/s) is modelled. The results show that the side openings of the configuration do not have an adverse effect on the discharge of the chimney. The results also indicate that the split chimney is able to slightly dilute toxic flue gases. The main drawback of the configuration is the side leakage. The wind direction and the geometry of the selected configuration were somewhat arbitrary. Geometry optimization and further studies are required to improve the performance of the split chimney.

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