

Dilution of toxic gases and smoke emissions from residential chimneys using a low-cost cap

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Abstract

Smoke and toxic gases emitted from chimneys present health hazard. Their concentration should be minimised before reaching the ground. The wind lowers the concentration before it reaches the surface. However, heavier than air toxic gases flow downward which is particularly problematic in the case of low wind speeds in high-density populated areas. Two effective solutions are to extend the height of the chimney or to employ a filter but generally these solutions are not practical or economical for residential applications. An innovative low-cost chimney cap is proposed to dilute toxic gases within the chimney before ejection. The configuration of the cap is inspired from chambers which are currently used to generate fire-whirl in the laboratory. The cap consists of two identical half cylinders which are placed off-centre at the top of the chimney. The previous experiments indicate that the entrained air swirls around the central vertical axis of the chamber and generates a whirling motion. The chimney discharge and the exhaust concentration are computed by modelling the cap. The computational results indicate that such a configuration not only is able to reduce the concentration of the discharge, but also is able to increase the discharge at low wind speeds.

Introduction

The recent introduction of the carbon tax has increased the cost of electricity which in turn would increase the use of fireplace and low-cost heating fuels. This increase would have an adverse impact on air quality similar to what occurred in early 1970s [6]. The combustion by products could include particulates, nitrogen oxides, sulphur oxides, carbon monoxide, and polycyclic organic materials [5]. The amounts and nature of emissions into the atmosphere depend on many factors such as operating conditions, fuel type, and combustor designs. Previous research show the adverse effects of the emissions such as bronchial asthma, chronic lung disease, respiratory illness, increase of infection rates, irritation of the eyes, lung cancer, and carcinogen in animals [5]. Several studies indicated that wood-burning stoves and fireplaces are potential hazards and are likely to pollute indoor as well as outdoor air. A research shows that about 70% of the outdoor wood smoke re-enters the house and nearby buildings [5]. Australia has already one of the highest rates of prevalence of asthma symptoms in the world [4]. The newly-introduced carbon tax might actually increase this rate due to possible increase of smoke and toxic gas emissions in densely populated residential areas.

Although chimneys discharge combustion products into the atmosphere, many factors such as insufficient stack height facilitate the access of smoke and toxic gases into the indoors [5]. It should be noted that even the newest airtight wood stoves emit a substantial amount of fine particles into the atmosphere [5]. The existing techniques to reduce the amount of harmful

emissions from chimneys include waste gas-purifying devices, fans and ducts, water curtains, steam curtains, greenbelts around the boundary walls of the chimney, and deliberate setting fire to a combustible gas release. However, these techniques are not used in the residential buildings primary due to their cost. Dilution with air by means of tall chimneys is perhaps the best approach for dealing with the issue. However, this technique also suffers from some limitations such as higher installation and maintenance cost. In addition, it should be noted that at low wind speeds, the heavier than air emissions hit the ground before sufficient dilution occurs regardless of the height of the chimney.

In a recent study, the performance of split chimneys has been investigated [9]. A split chimney is a simple and a low-cost configuration which can induce swirling flow within the chimney without any need of fan/blower. Previous research also shows that the discharge rate of a split chimney is slightly more than that of a conventional chimney. According to the study, split chimneys are able to moderately dilute emissions of chimneys [9]. However, they experience side leakages particularly at higher wind speeds. In another research study, the effects of wind direction on the performance of a split chimney were investigated [8]. The results show that the side leakage can be prevented by placing the split chimney in the right direction. However, this approach is only applicable if the wind direction is known. This limits the use of split chimneys to the areas with steady wind direction. It is important to note that both the previous research show that the side leakage does not occur in the lower parts of the split chimneys.

In light of this fact, the present work is an attempt to determine the performance of the split cap in terms of diluting harmful gases before entering the environment. The split cap has a shorter height and can be placed at the top of the conventional chimney. The main potential advantage of using split caps is the lack of side leakages. They are also expected to increase the chimney discharge rate, to generate swirling flow within the chimney similar to that induced by split chimneys, and to dilute the toxic gases within the chimneys. In addition, they have lower cost than split chimneys.

The present computational study determines the performance of three chimneys. The first chimney is a conventional chimney without a split cap and its discharge rate is computed and compared with that estimated from theory. The second chimney is a conventional chimney with a short split cap at the top. The height of the second chimney plus its cap is the same as the first chimney. The third chimney includes a conventional chimney and a long split cap. The total height of the third chimney and its cap is also equal to the first chimney. The third configuration provides an opportunity to assess the effects of the height of the split cap on the performance of the chimney.

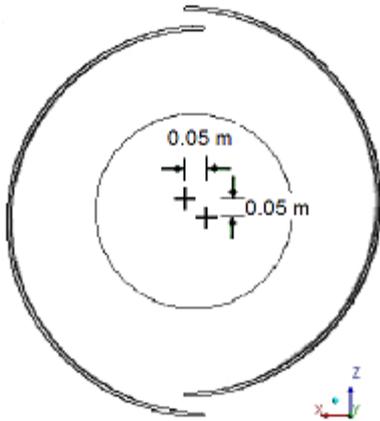


Figure 1 Top view of the split cap

Modelling

Three chimneys are modelled. The first chimney represents a conventional chimney with an internal diameter of 0.5m, a height of 3m and a wall thickness of 0.01m. The second chimney consists of a conventional chimney similar with the first chimney but with a height of 2.7 m. It includes a cap which consists of two identical half cylinders which were cut from a pipe along its central axis. The pipe had a height of 0.3 m, an internal diameter of 0.98 m and a wall thickness of 0.01 m. The two half hollow cylinders are placed 0.071m off centre, 0.05m in each horizontal direction (see figures 1 and 2a). The third chimney is similar with the second chimney but the height of the chimney and its cap are 2 m and 1 m, respectively (see figures 1 and 2b). The conventional chimney is modelled to verify the accuracy of the computational work. The computational domain is a cube, 50 m on a side. In all cases, the chimney is placed in the centre of the base of the computational domain.

The number of computational elements that is necessary for a converged result varies among chimneys. For the conventional chimney, 1145143 tetrahedral elements are used. Figure 3 shows the surface mesh around the split chimney. For the short split cap (the second chimney) and the long split cap (the third chimney), 1815329 and 1281405 tetrahedral elements are used,

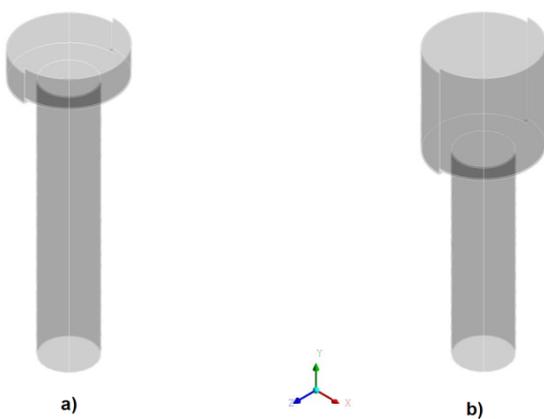


Figure 2: chimney with the split cap a) long cap; b) short cap

respectively. In all cases, the elements sizes vary from 5 mm around the chimney to 1000 mm near the domain boundaries.

In practice, the composition of combustion products differs for different fuels. In this work, the products are given the properties of air. The air is considered to be an ideal gas and its thermodynamic properties vary with temperature. The walls have no slip boundary conditions and are assumed to be smooth and adiabatic. Thermal radiation is not modelled. The ambient temperature is assumed to be constant (25° C) but hydrostatic pressure decreases with height using the following formula [7], Pozrikidis, 2009),

$$p = p_0 e^{\left(\frac{-g \cdot y}{R \cdot T_0}\right)} \quad (1)$$

where

P pressure, (Pa)

p_0 reference pressure, (101325 Pa)

R air constant, (287.1 J/kg/K)

T_0 reference temperature, (298.15 K)

y height with respect to the reference point, (m)

All sides of the computational domain except the bottom surface are set as “opening” boundary condition. The opening boundary conditions are used when the pressure is known but the direction of flow is unknown. The specified pressure is assumed to be static pressure if the flow is travelling out of the domain but in the case of inflow, the specified pressure is assumed to be the total pressure. The wind speed is zero in all cases and the static temperature is defined as 25 °C. The hot air inlet at the base of the chimney is defined as “inlet”. The total relative pressure and temperature are taken to be 0 Pa and 100 °C, respectively.

The governing equations are continuity, thermal energy, and Navier-Stokes equations. The Boussinesq approximation is not used due to large difference in temperature between the inlet air (100 °C) and the ambient air (25 °C). The thermal energy equation which is suitable for low-speed flows is used. The flow, particularly near the top of the chimney, is expected to be turbulent. Previous studies based on the k-ε model indicate good agreement with experimental results [10]. A modified version of the model (ReNormalization Group or RNG) is used. In the RNG model respect to the standard k-ε model, values of some

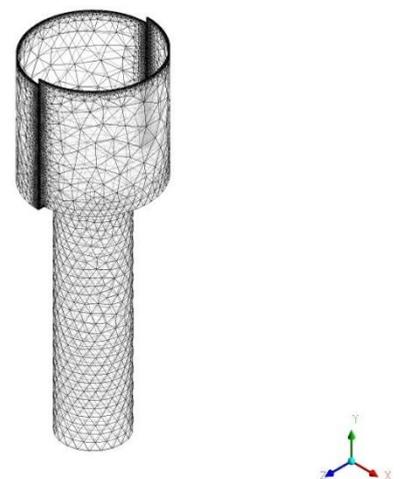


Figure 3: Surface mesh of the long split cap

constants are changed in order to improve the results [1].

The simulation was run using the high resolution scheme. The convergence criteria for all the variables (velocity components, mass, energy, k and ϵ) are taken to be 0.0001 based on RMS residuals. Two methods are introduced to evaluate the robustness and the accuracy of the results. In the first method, the number of the elements is increased by 10% and the results are compared. In the second technique, the results for the conventional chimney are compared with those obtained from the formulas found in the literature. Both techniques verified the results.

Results

The results of the modelling are presented in table 1. The inlet velocity and mass flow rate of air at the base of the conventional chimney are 3.616 m/s and 0.660 kg/s, respectively. The inlet and outlet velocity don't show any swirling motion, as expected. The accuracy of the results is compared with those available in literature. The following equations [2, 3] are used to calculate the discharge of a conventional chimney;

$$\Delta p = g(\rho_o - \rho_i)\Delta h \quad (2)$$

Where

g gravity, (m/s²)

Δh height of the chimney, (m)

Δp pressure difference between the top and the base of the chimney, (Pa)

ρ_i density of the air within the chimney, (kg/m³)

ρ_o density of the air outside of the chimney, (kg/m³)

The density and velocity of the air within the chimney and the major loss coefficient can be calculated as follows;

$$\rho = \frac{1.293 \times 273}{T} \quad (3)$$

$$\Delta p = \left(f \frac{\Delta h}{d_h} + \sum k_i \right) \frac{V^2}{2} \rho \quad (4)$$

$$\frac{1}{\sqrt{f}} = -2.0 \log \left(\frac{e/d_h}{3.7} + \frac{2.51}{Re \sqrt{f}} \right) \quad (5)$$

Where

d_h hydraulic diameter of the chimney, (m)

e roughness

f major loss coefficient,

k minor loss coefficient,

Re Reynolds number

T temperature, (K)

V air velocity within the chimney, (m/s)

ρ density, (kg/m³)

In this case, the inside and outside temperature of the chimney are assumed to be 100 °C and 25 °C, respectively. Using equation 3 gives the inside and outside density of 0.9464 kg/m³ and 1.1845 kg/m³, respectively. Equation 2 gives the pressure difference of 7 Pa. The minor loss coefficient is assumed to be one for the sudden expansion of the flow at the top of the chimney [3]. The major loss coefficient is calculated to be 0.019 using Colebrook equation (eq. 5, [3]). The inlet air velocity is calculated, using eq. 4, to be 3.65 m/s which is very close to the results of the modelling (3.616 m/s, see table 1).

Table 1: The results of modelling for the conventional chimney, the chimney with the short split cap, and the chimney with the long split cap.

| | no cap | short cap | long cap |
|--|--------|-----------|----------|
| Inlet mass flow rate, (kg/s) | 0.660 | 0.643 | 0.686 |
| Velocity at inlet, (m/s) | 3.616 | 3.519 | 3.755 |
| Total mass flow rate from the side gaps, (kg/s) | 0 | 0.009 | 0.078 |
| Velocity. Curl Y at bottom centre of the cap, (s ⁻¹) | N/A | 0.000 | 0.057 |
| Velocity. Curl Y at the middle centre of cap, (s ⁻¹) | N/A | 0.013 | 1.095 |
| Velocity. Curl Y at the top centre of cap, (s ⁻¹) | N/A | 0.034 | 0.071 |

Figure 4 shows the effects of the short cap on the streamlines originating from the inlet and the streamlines emanated from the side gaps which are coloured by velocity magnitude. The figure shows that the short cap is able to induce a weak swirl at the centre top of the cap. In this case, the inlet velocity and mass flow rate drop from 3.616 m/s and 0.660 kg/s to 3.519 m/s and 0.643 kg/s respectively, showing a decrease of 3%. The mass flow rate from the side gaps is 0.009 kg/s, indicating 1.4% dilution. $(0.009/(0.643+0.009) \times 100)$.

Figure 5 shows the effects of the long cap on the air movement. The streamlines are coloured similar to the previous case. The long cap is able to generate a comparatively moderate swirl at the top centre of the chimney. A maximum velocity curl Y of 1.095 s⁻¹ is observed at the height of 2.5 m. The results also show that the inlet air velocity and mass flow rate increase from 3.616 m/s and 0.660 kg/s in the case of the conventional chimney to 3.755 m/s and 0.686 kg/s for the long cap chimney, demonstrating a 2% increase. The inlet air mass flow rate from the side of the split cap is about 0.078 kg/s which represents a dilution of 10.6%.

Discussion

Three chimneys were modelled, a conventional chimney, a chimney with a short split cap, and a chimney with a long split cap. In all cases, the combined heights of the chimneys and caps were equal. The calculated discharge of the conventional chimney is very similar to that obtained from the theoretical formulas. The short and long split caps could induce a swirling flow within the chimney. The swirling movement increases with the increase of the height of the cap. However, in the case of the short cap, the swirling effect is insignificant and discharge through the chimney slightly decreases due to the disturbance produced at the top of the chimney. The level of dilution is also negligible (1.4%). The discharge of the chimney with the long cap indicates a moderate increase in comparison with that of the conventional chimney. A comparatively strong swirling flow was induced which could moderately dilute the combustion products inside the chimney (10.6 %).

Conclusions

The effects of two split caps with different heights on the performance of a chimney were studied. The results show that both split caps are able to draw in fresh air from the side gaps and induce swirling flow within the chimney. A long cap slightly increases the discharge of the chimney while a short cap decreases it. The level of dilution of the emissions increases with the height of the caps, however, even in the case of the long cap; it does not exceed 10.6%. The performance of the split cap requires further investigation in order to increase dilution of the combustion products and minimize its environmental impact.

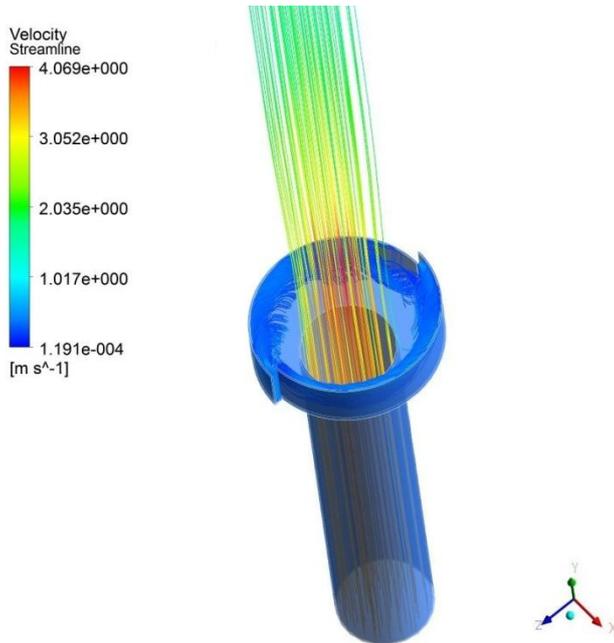


Figure 4: streamlines around the chimney with the short split cap

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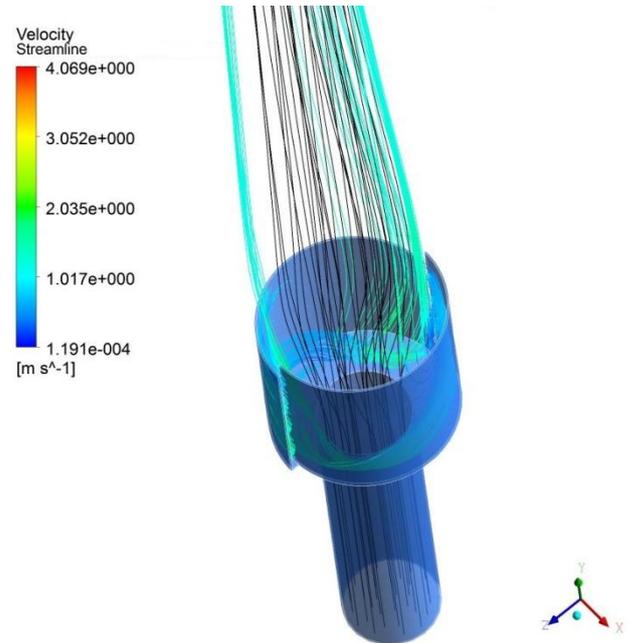


Figure 5: streamlines around the chimney with the long split cap

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