

Determining the venting efficiency of simple chimneys for buoyant plumes

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ABSTRACT

We present preliminary results from an examination of the capture and venting of a buoyant plume by a chimney. The aim is to enable improved management of indoor pollutant sources – for instance, the plume rising from a cooking pan in a kitchen or a cooking fire in a hut. Using the principle of dynamic similarity, we precisely and controllably model the behaviour of indoor plumes by using saline solutions ejected into an enclosure containing freshwater. These well-established laboratory analogue techniques enable the location and concentration of tracer in the plume to be easily tracked, reflecting the evolution of pollutants carried in the plume. Focusing on a plume within a room containing a quiescent ambient environment, we identify two physical mechanisms potentially responsible for driving the removal of pollutants. The first, we describe as the *capture* of the plume, a process driven by the direct interaction between the plume and the evacuation opening; the second, we describe as the *draining* flow driven by a buoyant layer of fluid which may accumulate at the ceiling and is then evacuated through the effects of buoyancy. We first demonstrate that the addition of a simple cylindrical chimney that hangs downwards from an opening in the (analogue) ceiling increases the venting efficiency of these potentially polluting plumes. We go on to examine how the capture efficiency of these simple chimneys varies as the relative size of the plume and the chimney are altered, and demonstrate that simple model can provide predictions of the observed variation in capture efficiency.

KEYWORDS

Cooking smoke plumes, Indoor air quality, Ventilating cooking fumes.

1 INTRODUCTION

Indoor air pollution is a serious public health concern affecting the lives of many people in developing regions around the world; especially so, when the degradation of indoor air quality results from combustion for cooking and heating. In India, for example, cooking frequently takes place indoors on inefficient ovens or open fires that burn solid fuels typically comprised of wood, coal, crop residue and cow dung (WHO 2014). When burned, these materials produce dangerous pollutants that are inhaled by those indoors, particularly those doing the cooking – frequently women accompanied by their youngest and most vulnerable children. Regular

exposure to the pollutants from this indoor combustion increases serious health problems such as the risk of young children contracting pneumonia, chronic obstructive pulmonary disease, and further increases the risk of lung cancer and strokes. Issues related to indoor air quality are estimated to lead to 1.7 million premature deaths per annum in South East Asia alone, therefore constituting a major health concern in the developing world (WHO 2014). The pollutants from indoor combustion are carried within plumes of warm smoky air, herein cooking plumes, which rise and develop within the room or hut. We report results from a preliminary investigation of a method to encourage the more efficient evacuation of these cooking plumes.

In more developed regions of the world, cooking on open fires indoors is atypical and any indoor combustion occurs using relatively clean fuels and burners. However, the act of cooking produces odours and particulates that may not only be undesirable but also significantly degrade indoor air quality. The results reported herein have potential application to the cooking plumes rising above pots, pans or burners in more modern kitchens.

In rural parts of the developing world, cooking is frequently carried out relatively centrally within a room or hut and the cooking plume is ultimately evacuated through an opening made by removing a small portion of the ceiling and roof. However, as these cooking plumes rise their mass (or volume) flux increases rapidly due to the entrainment of the room's ambient air and so whilst a portion of the cooking plume may be directly evacuated through the opening in the ceiling there is also potential for a portion of the cooking plume to accumulate at the ceiling forming a layer of warm smoky air within the room – chronic exposure to which is extremely detrimental to human health. We investigate the effectiveness of enhancing the evacuation of these cooking plumes, with a view to reducing the layer of warm smoky air within the room, by the introduction of a thin-walled cylindrical chimney.

For simplicity, we consider cases in which the act of cooking is the only heat source and the effects due to any external wind, or draughts within the room/hut, are negligible. It has long been established that in such cases, the dynamics of buoyant (herein cooking) plumes are self-similar and may be predicted by considerations of the conservation of the fluxes of mass, momentum and buoyancy; with the assumption that the (horizontal) entrainment of ambient fluid at the plume edge occurs at a velocity which is related to the local vertical velocity in the plume by a constant entrainment coefficient, α (Morton *et al.*, 1956). Utilising this 'plume theory' and the principles of dynamic similarity we create experimental analogues of these cooking plumes and carry out a laboratory study of saline plume in freshwater environments.

The momentum flux (due to the work done by the buoyancy flux) associated with the cooking plume as it reaches the ceiling can be utilised to drive an evacuating flow directly through the opening in the ceiling, a process that we describe as the *momentum capture*. We consider cases where the centre of the plume source is aligned with the centre of the opening, such that the portion of the plume that might be directly captured through this process might be predicted. In the practical example under consideration, illustrated in figure 1a, any portion of the flux of pollutants produced by cooking (the buoyancy flux of the cooking plume) that is not directly evacuated by momentum capture then accumulates at the ceiling, forming a warm upper layer of smoky air within the room – the buoyancy of this warm layer acts to drive a *draining* flow and further contribute to the evacuation of the polluting smoke from the room.

In our analogue laboratory experiments, we introduce a chimney, consisting of a thin-walled cylindrical perspex tube, open to flow at both ends that 'hangs' within the space representing the room. The chimney is temporarily fixed to the laboratory analogue of the room's ceiling. We carry out experiments to demonstrate that the polluting cooking plume can be more effectively evacuated by the addition of a chimney within the room. We develop experiment

procedures to measure and the capture efficiency of a chimney in a given set-up and describe these methods in Section 2.

In order to establish an experimental set-up that allows for both the momentum capture and draining of the plume we first introduce a *holed chimney* which had a number of holes drilled in its side walls at a height just within the ceiling of the room. That is, the momentum flux of the plume at the entrance to the holed chimney (closest to the plume source) enabled the buoyancy flux (representing the flux of cooking pollutants) to be ‘captured’, whilst any buoyant fluid accumulating at the (laboratory analogue of the) ceiling could be ‘drained’ through the holes drilled in the chimney side-walls. We discuss the results for these cases in Section 3.1. We then focus on the process of ‘capture’ by the chimney by eliminating the draining process by using a *simple chimney*. We show that a simple model is able to predict the capture efficiency of simple chimneys in Section 3.2. Finally we draw conclusions, discuss their implications and highlight future directions for the research in Section 4.

2 EXPERIMENTS AND METHODS

Exploiting the principles of dynamic similarity, we create laboratory analogues of the cooking plumes, of interest to this study, by ejecting saline solution downwards within a clear Perspex visualisation tank. We ensure that density differences between the saline plume and its freshwater environment were relatively small, akin to those arising due to the temperature difference between a cooking plume and the ambient air within a room. Hence, the dynamics were Boussinesq and the physics notionally identical for a cooking plume rising within a room and a dense saline plume falling within a freshwater environment.

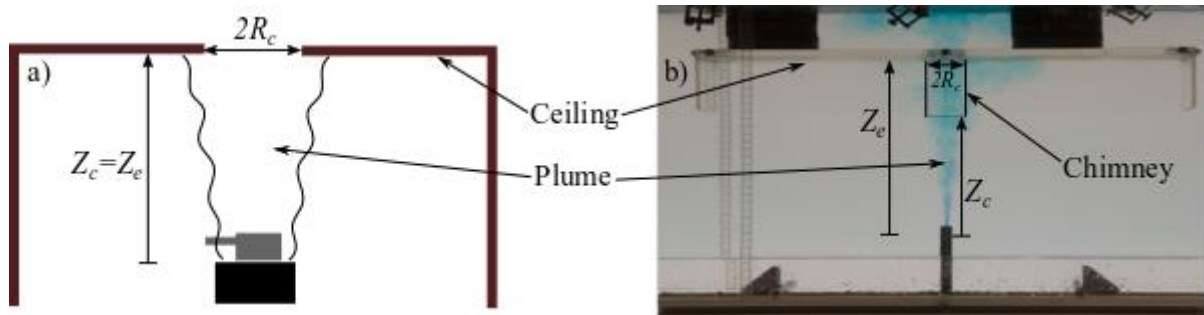


Figure 1: a) Illustration of a cooking plume rising in a room/hut and being evacuated through an opening in the ceiling; b) Experimental image of a saline plume (inverted for ease of comparison) being evacuated through a simple chimney.

To enable visualisation, and ultimately determine the effectiveness of adding a chimney, the saline plume was stained using methylene blue as a dye. The experimental set-up was backlit using a sheet of white perspex to diffuse the light from four halogen spotlights and images were recorded using a Nikon digital SLR camera. Figure 1 shows an illustration of a cooking plume being evacuated from a room or hut, and an experimental image (inverted for ease of comparison) of a saline plume with a simple chimney added. Dyed saline solution (of known density, measured using an Anton Paar densitometer) was pumped (using an Ismatec gear pump) through a circular plume nozzle of radius $r_0 = 0.25\text{cm}$. The flow rate was set such that the ratio of inertia to buoyancy attained the invariant ‘pure plume’ balance (Morton *et al.*, 1956) close to source. As such, all vertical distances are measured from a ‘virtual origin’ located a distance $5 r_0/(6\alpha)$ behind the source, with $\alpha = 0.11$ taken throughout as appropriate for a top-hat plume (see Section 2.1).

Following the methods and procedures detailed by Allgayer & Hunt (2012) we used the light attenuation technique, whereby the integral dye concentration along light paths received by the camera sensor can be inferred from the amount of light attenuated by the dye (relative to an image taken in the absence of any dye). Attaching four Perspex walls to the experimental ‘ceiling’ formed a tray in which the dyed saline, that was not directly evacuated, was able to accumulate. By summing the inferred integral dye concentration over light paths representing the viewing area of the tray the total mass of dye in the tray could be estimated and from our calibration data we were able to relate these to estimates of the total buoyancy accumulated within the tray, which denote B . From this, we could then define the capture efficiency as

$$CE = 1 - \frac{B}{F_0 T}, \quad (1)$$

where F_0 is the plume buoyancy flux (prescribed at the source and physically conserved throughout the plume) and T denotes the time since the experiment commenced.

It is important to note that throughout, including in equation (1), we make no account for the draining process whereby fluid that accumulates at the ceiling is able to be evacuated due to the action of buoyancy. In Section 3.1, we do report results from a deliberately limited set of experiments in which the draining process is feasible - results that are only included to illustrate the effectiveness of adding a chimney to the application considered herein (figure 1a). Moreover, for the results reported in Section 3.1 the capture efficiency is calculated only for time periods over which the additional evacuation due to the draining process (which requires a meaningful accumulation of buoyant fluid at the ceiling) might be expected to be negligible – we show, in section 3.2, that this is the case for the experiments with the holed chimney.

One would expect that the capture efficiency might vary depending on a number of factors; not least, with the given capture area (determined by the radius, R_c , of the chimney or the opening in the ceiling) relative to that of the plume. The characteristic radial scale of a plume is known to increase linearly with the distance from the source, such that their (time-averaged) flow envelope forms and expanding cone. Given that the dynamics of plumes are self-similar, one can investigate the effects of the relative size of the chimney simply by using a single chimney, in our case of diameter $2R_c = 3.4\text{cm}$, and then varying, for example, the vertical separation between the virtual source the chimney opening, Z_c (see figure 1). We denote the height of the chimney L and examine single chimney of aspect ratio $L/2R_c = 2.35$. We denote the vertical distance between the virtual source and the ceiling Z_e . We choose to express distances from the virtual source in terms of a characteristic radial scale for the plume, defined $R_T(Z) = (6\alpha/5) Z$, in so doing we are able to compare the physical scale of the plume (dependent only on the distance from the virtual source) to that of the chimney.

2.1 Two models for estimating the capture efficiency

Using plume theory, one can derive simple estimates for the portion of the buoyancy flux in an axisymmetric plume that might pass through a circle, or radius R_c , positioned a vertical distance Z from the virtual source. Herein, we consider two simple models, one assuming that the distribution of velocity and buoyancy within the plume follows a uniform distribution – the top-hat plume model; the assuming that the distribution of velocity and buoyancy within the plume follow a Gaussian distribution – the Gaussian plume model. One can then examine predictions for a top-hat capture efficiency, defined as

$$CE_T = \frac{2\pi \int_0^{R_c} r w_T b_T dr}{F_0}, \quad (2)$$

where r is the radial coordinate, F_0 is the plume buoyancy flux, w_T and b_T are the velocity and buoyancy in the plume assuming top-hat distribution – full analytic expressions for which are

presented by Morton *et al.*, (1956). In addition we examine predictions for a Gaussian capture efficiency, which we define as

$$CE_G = \frac{2\pi \int_0^{R_c} r w_G b_G dr}{F_0}, \quad (3)$$

where w_G and b_G are the velocity and buoyancy in the plume assuming a Gaussian distribution – full analytic expressions for which are presented by (Baines & Turner, 1969).

3 RESULTS

3.1 Demonstrating the effectiveness of adding a chimney

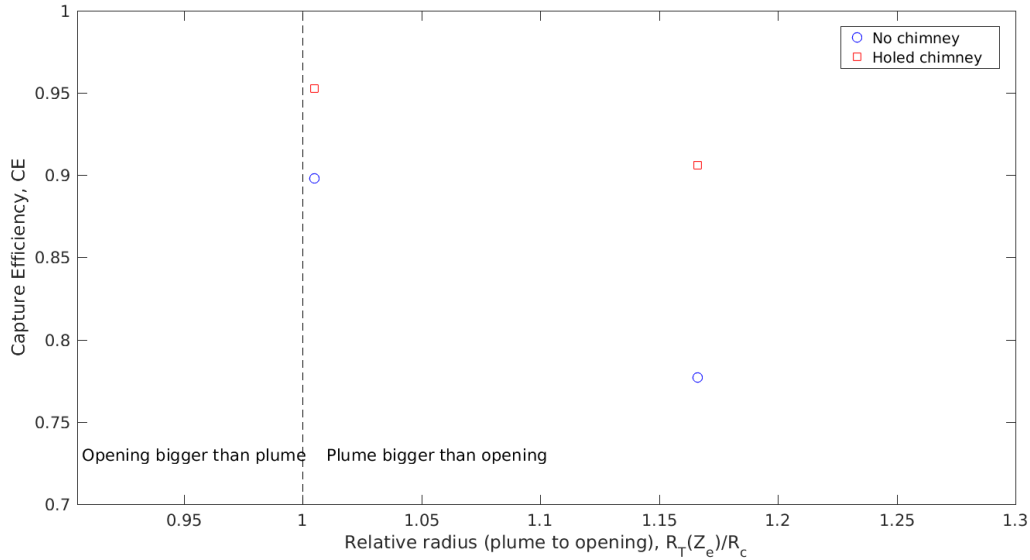


Figure 2: The capture efficiency for two different relative sizes of the chimney and plume. Data is presented without a chimney, typical in current application, and with the addition of a chimney which markedly increases the capture.

To compare situations to those currently found in practice (figure 1a), we ran two experiments in the absence of a chimney and varied the distance between plume source and the ceiling in each – this mimics the effect of changing the radius of the opening in the ceiling. With the radius of the opening approximately equal to the top-hat radius of the plume our data showed around 90% of the buoyancy flux was evacuated by momentum capture. This capture dropped to less than 80% when the radius of the opening was just 15% smaller than the top-hat radius of the plume (figure 2). Crucially, in both cases, figure 2 shows that keeping the distance between the source and the ceiling fixed, and then adding the holed chimney markedly increased the momentum capture of the plume. For our examples, the addition of the chimney approximately halved the buoyancy flux that would accumulate at the ceiling, indicating the potential exposures to any pollutants carried by the plume may be drastically reduced by the addition of a chimney. We note that for these preliminary experiments we tried to minimise the effects due to the draining of buoyant fluid at the ceiling; figure 3 shows that the effects of draining were negligible for the experiments with the holed chimney.

3.2 The variation of the capture efficiency with the relative chimney radius

In order to examine the capture efficiency of a chimney we carried out experiments using a simple chimney for which all fluid not directly captured remained within an impermeable tray.

We systematically varied the distance between the source and the entrance to the chimney, mimicking the effect of varying the radius of chimney. Chimneys of radius approximately 30% larger than the plume top-hat radius ($R_T/R_c \sim 0.7$) were found to capture almost the entire buoyancy flux of the plume. As one might expect, the capture efficiency decreases as the relative size of the chimney decreases. Crucially, figure 3 shows that predictions of the capture efficiency from the Gaussian model agree relatively well with the experimental data, suggesting that perhaps this simple model can be used to predict the evacuation of a plume by the process of momentum capture.

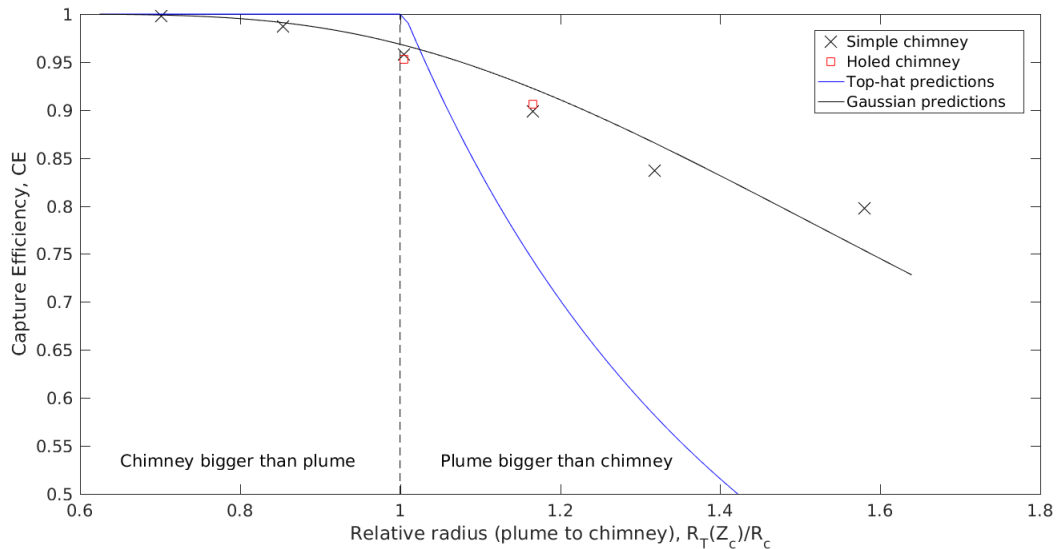


Figure 3: The variation in capture efficiency for different relative sizes of the chimney and plume. Our experimental data is marked at discrete locations and the theoretical predictions of the two models, (2) and (3), are overlaid.

4 CONCLUSIONS

The addition of a basic chimney hanging from an opening within a ceiling has been demonstrated to increase the direct capture of buoyant plumes. This suggests that an affordable chimney, which could be simply formed from sheet metal and hung downwards from the opening in the ceiling, offers the potential to reduce exposure to the polluting smoke from cooking and/or heating within rural homes in the developing world. Our experiments further show that the portion of plume fluid evacuated by the mechanism of momentum capture can be simply predicted with a satisfactory degree of accuracy. In so doing, we provide a first step towards being able to reliably predict the exposures to pollutants due to combustion in rural homes both in the absence and presence of a chimney hanging downwards into the room.

That said, we do not underestimate the scale of the work that remains in order to make meaningful predictions in the cases of real application. Thus far, we have not examined the effects of the evacuation due to the buoyancy driven draining of any layer of warm fluid at the ceiling. Moreover, we have not examined the effects that varying the length of the chimney might have, for example potentially reducing the capture due to viscous effects in the presence of the chimney, or enhancing the capture due to the stack effect of the buoyancy. Finally, all of the above neglects the effects of external winds and the resulting internal draughts that are likely to play a significant role in these relatively permeable rural buildings. However, we regard this as a fruitful and rewarding avenue on which to continue future research.

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