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計畫主持人：林嘉明
共同主持人：陳志傑，馬一中
計畫參與人員：楊慈定，黃明豐

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.行政院國家科學委員會補助專題研究計畫

☑ 成果報告
□期中進度報告

拜香燃燒煙污染物的控制
Control for Incense Smoke Pollutant

計畫類別：☑ 個別型計畫　　□ 整合型計畫
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成果報告類型(依經費核定清單規定繳交)：□精簡報告　☑完整報告

處理方式：除產學合作研究計畫、提升產業技術及人才培育研究計畫、列管計畫及下列情形者外，得立即公開查詢

□涉及專利或其他智慧財產權，□一年□二年後可公開查詢

執行單位：國立台灣大學公共衛生學院環境衛生研究所

中　華　民　國　94 年　10 月　31 日

摘要

本研究探討拜香熱值(A，B，C，D種拜香熱值 3936-5060 Kcal/Kg)、化學組成（碳 45-65%及揮發份 20-80％）、拜香粗細（3-5mm）及燃燒環境條件(流量率與含氧量)等對氣相和微粒相燃燒生成物排放的影響，以利低污染拜香的研發。研究在可控制燃燒環境的試驗腔進行，控制試驗腔的流量率（1~20 L/min）與含氧量（20％-45％），令拜香處於悶燒至明火燃燒的狀態，在各次試驗（trial）時分別以直讀式儀器測量燃燒點的表面溫度以及測試腔內微粒的粒數濃度、體積濃度、粒徑分佈、CO、CO_2與TVOCs，另外並使用閉口式濾紙夾搭配 37 mm 石英濾紙採取總懸浮微粒後稱重分析和使用活性碳吸附管採取揮發性有機污染物，藉氣相層析質譜儀定性和定量有機化學物質；計算拜香的燃燒率（g/hr）與燃燒效率（=[CO_2/(CO+CO_2)]），以及各類氣相物質及微粒相物質的排放（速）率（mg/hr 或particle number/hr）與排放因(數)子 (mg/g 或particle number/g)。

無煙香原料含揮發份較低，有煙香原料含揮發份相對高，但後者熱值（kcal/g）略低。原物料熱值愈高，拜香轉為火焰燃燒的所需含氧量越低，但無論何種拜香，當溫度超過大約 650 ℃時瞬即轉為有火焰燃燒，之前悶燒的溫度介於自 400 升到 650 ℃。當拜香悶燒時，在相同的環境因素（空氣含氧量及流量率）下，高熱值拜香的燃燒點表面溫度較高，粗的拜香燃燒點表面溫度亦較高；燃燒點溫度，也會分別隨著補充空氣的含氧量與流量率的增加而升高，但流量率超過 15 L/min時開始有明顯的冷卻至溫度持恆（210 ℃）的效應。同一種拜香當燃燒點溫度升高時，燃燒率以及CO、CO_2、TVOCs及微粒的排放率與排放因子亦遞升，燃燒率以及氣體及微粒的排放率之自然對數值分別與燃燒點絕對溫度的倒數成良好的線性關係；至於兩種拜香比較，無煙香原料含揮發份較低，熱值（kcal/g）相對高，燃燒點表面溫度亦較高，CO、CO_2的排放因數子（mg/g）相對的高，TVOCs排放因數子相對的低，產生較低的微粒濃度（質量濃度與粒數濃度），而粒徑中位數亦相對的較小。至於同種拜香，粗的產生較多的粒數濃度，而且同種拜香在流率為 15 L/min以下時，隨著流率增加粒徑變小而數目增加，但無論如何粒徑份佈均在次微米下。

未經燃燒的 A(檀香)、B(無煙香)與 C(檜香) 等拜香溶劑萃取液分別被鑑定出 25、19 與 84 種有機化學物質。大量的是天然植物性香料貢獻的烷、烯、醇、酚及其衍生物、醛、酮、及酯類，亦含少量可能是由動物性香料貢獻的如出現於拜香 C 之麝香 (musk)。當作塑化劑用的 diethyl phthalate 和 bis(2-ethylhexyl)phthalate 也出現在拜香的溶劑萃取液。拜香燃燒所產生的微粒相有機污染物，部分源自於原物料中的原形（低揮發性有機物）蒸發後再凝結在微粒表面，部分為真正燃燒的產物。悶燒拜香所產生微粒相高碳分子量有機物，隨燃燒時含氧量的增加而上升，但轉為火焰時，被高溫破壞而迅速下降。另外，悶燒拜香低碳數烷類有機污染物，隨含氧量的增加，呈現下降的趨勢，因為低溫下產生較多量低碳數的烷類，隨溫度的升高，低碳數的烷類量的減少可能是被高溫進一步破壞。在氣相所見的有機

揮發物，其狀況亦十分相近。結論認為低含碳量及揮發物的原料所製成的細拜香，在較低的氣體流量率之下使用，會產生相對低的 TVOCs、微粒及微粒像有機化合物。

關鍵詞：拜香、悶燒、燃燒煙、次微米微粒、微粒相有機化合物

Abstract

To develop a less polluting incense, this study characterized the gaseous and particulate emission from burning four types of Chinese incenses (A, B, C, D) with different heat values (3936-5060 Kcal/Kg), chemical compositions (carbon content 45-65% and volatile component 20-80%) at the controlled atmospheric conditions (air flow rate and oxygen content of air). The experimental trials were conducted in a test chamber where air flow rate (1-20 L/min) as well as oxygen content (20-45%) was regulated to keep incense smoldering up to burst of flame burning . The direct reading instruments were employed to measure the surface temperature at tip of a burning incense, characteristics of particulates (number concentration, volume concentration and size distribution), and concentrations of CO_2, CO and total volatile compounds (TVOCs), respectively. The 37 mm quatz filter in a three pieces holder for sampling total particulates and the activated charcoal tube for sampling gaseous volatile organic compounds were applied to collect incense smoke for GC/MS analysis. The combustion rate (g/hr) and combustion efficiency ($=[CO_2/(CO+CO_2)]$) of an incense, and the emission rates (mg/hr or particle number /hr) as well as the emission factors (mg/g incense consumed or particle number /g incense consumed) for gaseous and particulate pollutants were calculated.

The so-called “less smoke incense” had greater amount of carbon, less volatile component and greater heat value in comparison to the “smoke incense”. The incense with greater heat value required less oxygen content to shift it from smoldering state to flame burning state. The temperatures at tip of a burning incense during smoldering ranged from 400 ℃to 650℃. The incense soon shifted to flame burning at temperature beyond 650℃. At atmosphere with fixed air flow rate and oxygen content, the smoldering incense with greater heat value had relatively high surface temperature at burning tip and the incense with greater diameter did as well. The surface temperature also raised with the increase of oxygen content and air flow rate, respectively. However, the cooling effect due to high flow rate beyond 15 L/min tended to keep the temperature around 210℃. The burning rate of an incense and the emission rates as well as emission factors for particulate, CO_2, CO and TVOCs increase with the increase of the surface temperature at burning tip. The linear regression was fitted well for the rate or the factor versus the inversely temperature in Kelvin. In comparison with the “smoke incenses” (types A, C and E), the “less smoke incense”(types B and D) with greater carbon content, greater heat value but less volatile component had relatively greater emission rates and emission factors of CO_2 and CO , less emission of TVOCs, less particulate concentration and smaller size of particulate. Within a group of incenses prepared by the identical raw materials, burning the coarse incense yielded greater number concentration of submicron particulates. The number concentration increased but the size of particulates decreased as the air flow rate increased from 1L/min up to 15 L/min.

GC/MS analysis identified 25, 19 and 84 species of chemicals in the solvent extracts of incenses A, B and C, respectively. Most chemicals such as alkanes, alkenes, alcohols, aldehydes, ketones, esters and phenols are likely attributed to the vegetarian raw materials of an incense while a few of chemicals like musk found in the extract of the Incense C may be from animal source. Plasticizers such as diethyl phthalate and bis(2-ethylhexyl)phathalate were also found in the extracts of the incenses. Particulate–bound chemicals found in incense smoke mainly were heat decomposed organic compounds although parts of the particulate-bound chemicals with low volatility were identical to the chemicals found in the extract of the incenses. The particulate-bound chemical species with greater carbon number increased along with the increase of oxygen content during smoldering of incenses but soon decreased as the incenses turned to flame burning. On contrary, the particulate-bound chemicals with less carbon number decreased with the increase of oxygen content in the supply air. The similar trends happened in gaseous phase of incense smoke. We concluded that the incense with low carbon content and less volatile component burning in atmosphere with low air flow rate yields less amount of pollutants in terms of TVOCs, particulates and particulate-bound chemicals.

Keywords: Incense, Smoldering combustion, Submicron particle, Particulate-bound chemicals

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一、緣起與目的

50％以上的台灣家庭有經常燃燒拜香習俗，暴露拜香燃燒煙的族群幾乎涵蓋所有的年齡層，尤其是居家時間相對較長的病人、老少、婦女等。拜香燃燒所產生的煙霧為複雜的混合物，包含氣相的化合物以及載有化合物的高數目濃度的細粒徑微粒，容易深入人體呼吸道系統之肺泡區，倘若拜香燃燒煙是健康的危害，則它將是與其他燃燒行為如抽煙一樣，成為受關心的公共衛生問題。

拜香因使用的目的與場合不同，而有不同形式與種類的商品：立香、環香、盤香、臥香、錐香、貢香、燻香粉等等。市面最常使用的立香(檀香)和單一香材原料所組成的臥香。立香主要分為香材粉末、染料、竹材、黏粉和也許會添加少許的精油所組成。貢香為立香的放大製品，環香、盤香、臥香、錐香與燻香粉則為原香材粉末製作成不同形狀的商品(不含中心竹材)。目前市售的環保拜香號稱完全使用天然原物料且過程不添加任何化學製品。

點燃拜香屬於固體表面燃燒的一種。當固態物質於空氣中燃燒時，氮或氧等助燃劑吸附於燃燒點表面，形成可燃物與助燃性分子的混合系。但是，一般固體的熱傳導率甚大，燃燒產生的熱急易散失，若非持續供給熱能不易發火，而成悶燒（smoldering），此時氧氣分子須穿透燃燒固體表面所產生的燃燒生成物層，始能持續供給助燃物於固體燃燒點表面，該燃燒生成物層的狀態，會干擾固體的燃燒速度。Moallemi 等人(1993)以二維數學模式解析木炭的 smoldering，顯示質量含氧率低於 13.5 %無法燃燒，含氧率介於 13.5~55 %發生 smoldering，且燃燒速率隨含氧量升高而加快，當含氧率超過 73 %會有火焰發生。不同之質量含氧率會影響燃燒點圓錐形之形狀，圓錐中心溫度最高離中心越遠溫度越低，中心含氧量最低，離中心越遠含氧量越高。

拜香長時間燜燒會產生煙霧狀的污染物，已知有氣相的一氧化碳、二氧化碳、氮氧化物、甲醛、多種揮發性與半揮發性有機化合物(多環芳香烴化合物)及其它等；以及固相的細粒徑懸浮微粒、其上吸附化學物質(Schoentol, 1967; Huynh, 1991; Lin and Wang, 1994; Lin and Tang, 1994: Lin and Lee, 1998; Chang et al., 1997)。其中微粒的粒徑分佈會因燃燒條件及環境因素而異，並且隨著在大氣滯留的時間及稀釋程度的變化有膠結變大趨勢，目前文獻所見大抵為粒徑介於 0.08-0.6 μm 的次微米的細微粒(Chen,1990; Fine,1999; Kleeman,1999; Kleeman, 2000)(Li et al., 1992; Li et al., 1993; Yaun et al., 1993; Cheng et al.,1995; 張 et al., 1999; 張 et al., 2000) ，是屬於可呼吸性的微粒有較高的機會到達人體肺泡區，並有較高的粒數濃度和表面積可以附著較多的有害物質。這些氣狀及粒狀污染物主要經由呼吸途徑進入人體，在肺的高濕環境下，其中的粒狀物可能吸濕長大而成微米以上的細微粒，提高其在肺的滯留率，如 Robinson 等人研究香煙燃燒煙之所見，0.1~0.4 μm 的香煙微粒，在肺的滯留率為 10~35 %，而當吸濕成長至 2~10 μm 時，滯留率提高為 47~97 %[Robinson et al., 1998]。按 Li 及 Hopke 所發展的預測模式，微粒粒徑在高濕環境成長的倍數，除環境的溫度與濕度之外，與組成微粒的可溶部分關係密切，可溶部分的比值高、水解離度大、平均分子量小等有利於粒徑的成長[Li and Hopke, 1993]。

個案報告指出長期接觸拜香燃燒煙曾經造成過敏性色素接觸性皮膚炎(Hayakawa,

1987)、搔癢性去色素斑點(Hayakawa, 1987b)的。癌症流行病學研究中，暴露拜香煙霧被懷疑可能和肺癌(MacLennan et al., 1977)、白血病(Lowengart et al., 1987)及腦瘤(Preston-Martin et al., 1982)的發生有所關聯，但亦有少數研究無法支持這個相關 (Chen et al., 1990; Ger et al., 1993)。。至於細胞毒理實驗則顯示：拜香燃放物中的多環芳香烴化合物（PAHs）及甲醛具有致突變性和細胞染色體變異的效應[Sato et al, 1980; Rasmussen et al,1987; Löfroth et al, 1991; Chen and Lee, 1996; Chang, Kuo and Lin, 1997]。

過去對拜香煙霧特性的研究皆是在燃燒條件未控制下進行，而相關的人類暴露資訊則常以問卷取代實測，燃燒環境條件和原料的組成對拜香燃燒特性生成物及暴露影響則鮮少探討，至於減少暴露的控制技術則更少。因此本研究群於 90 年度的相關研究計畫完成可以控制燃燒環境的測試系統，初步掌控燃燒環境與拜香燃燒生成物之間的關係，認為健康拜香的研發似乎應朝向低熱值、低碳含量、低揮發物的原料著手，但是必須進一步瞭解有機污染物生成的的資訊，另外為降低使用拜香的微粒危害有必要研發去除微粒的控制技術故本計畫案預定探討拜香燃燒物中揮發性有機物的生成及其在氣固相（微粒上）的分佈，累積拜香燃燒物的特性資料，以利進一步研發拜香污染的控制技術。具體的探討：(1) 氣流、拜香種類、拜香的粗細、氧氣含量、燃燒點表面溫度對拜香燃燒生成微粒與氣態污染物之影響 (2) 拜香原物料有機成分及其燃燒後釋放至空氣產物的變化 (3) 微粒相有機化學物質與氣相揮發性有機物的生成及其在氣固相的分佈 (4) 由悶燒轉折至火焰燃燒的機制及生成物變化。

二、材料與方法

1、選擇拜香

選取同一品牌拜香 A(檀香)、B(無煙香)與 C(檜香)三種拜香進行研究，拜香 A 與 B 為含有中心竹材的線香，拜香 C 為不含中心竹材的臥香，拜香 A 的粉末由三種植物所組成分別為 Santalum album L., Machilus nanmu Hemsl, 和 Pine oleoresin，拜香 B 並不知道組成的植物粉末原料，拜香 C 為檜木粉末所構成。

2、自製拜香

為探討不同粗細拜香對氣相和微粒相燃燒產物的影響，使用上述無煙香 B 和檀香 A 的原物料粉末分別製造拜香 D 和拜香 E。拜香 D 和拜香 E 不含中心竹材，分別有三種粗細不同的規格。製造拜香之步驟：以天平秤取黏粉和新山柴 1：4 之重量比，以杓子均勻混合之並平鋪於乾淨之桌面，沾水壓實捏成長約 35 公分、直徑相當（粗約 5mm、中約 4mm、細約 3mm）的線相，移到陽光底下晾乾而成粗細不同的拜香。自製拜香並未加入染料改變拜香之外觀顏色。

3、分析拜香的元素組成與熱值

對所選用的拜香，使用元素分析儀進行 C、H 及 N 元素分析，並使用熱卡計進行熱值分析。另外，亦對拜香組成燃材進行工業分析測試，測試項目包括灰份、水份、揮發份及固定碳。

4、分析拜香原物料萃取的有機化合物

將 A、B 與 C 拜香，以乾淨的剪刀，剪成細小的數段，經秤重量分別為 0.4876、0.3456 與 0.4510 g，分別放到 8 ml 茶色樣品瓶中，加入 5 ml 二氯甲烷，振盪 60 min，取出 1 ml 置於 1.8 ml 茶色樣品瓶，再加入 2 ng Anthracene-d10 當作內標，隨即以氣相層析質譜儀分析。所有樣本在採樣後一星期內分析完畢。氣相層析質譜儀分析的分析條件如下所述：分析管柱：Rtx-5MS，60 m × 0.32 mm × 1.5 μm。載送氣體流量為 1.0 ml/min。升溫程式：40 ℃，1.5 min→10 ℃/min→300 ℃，10 min。注射口溫度：300℃。GC/MS 介面溫度：300℃。不分流模式。質譜儀操作模式為掃瞄模式（scan mode），掃瞄範圍在 30～550 之間，溶劑延遲（solvent delay）時間為 5.2 min，Anthracene-d10 定量的離子 188。

5、建置燃燒測試系統

可控制燃燒條件的測試系統可供燃燒生成物的採樣分析。如圖 1，測試系統構造包括、拜香燃燒污染物產生單元、採樣測試腔。以下簡單說明此系統中的各單元結構：(1)拜香燃

燒物的產生單元：點燃的拜香置於內徑 2 cm、高度 15 cm的圓管內，調整拜香燃燒點的流率及含氧比率，令產生的氣態和微粒污染物測試腔中。拜香燃燒點的流率及含氧比率的調整，使用兩瓶高純度N_2和O_2的鋼瓶，分別經由調壓閥和HEPA去除微粒，再經由質量流量控制器分別控制不同N_2和O_2的流量進入氣體混合腔，讓N_2和O_2混和均勻，拜香燃燒點溫度的量測，使用鎳鉻和鎳鋁所製成的K-type Thermocouple，此時因為拜香燃燒時香枝會隨時間縮短，必須隨時調整拜香燃燒點高度，以維持拜香燃燒點位置。(2)採樣測試腔：拜香燃燒產生的氣態和微粒污染物進入採樣測試腔中，供採樣分析。採樣測試腔內徑 20 cm、高度 60 cm，可以在距離採樣測試腔底部 41 cm處進行微粒相污染物的採樣。另外，在不同氣流量的燃燒條件的測試系統的構造唯一改變為高壓空氣經HEPA去除微粒，經由質量流量控制器調控不同流量，導入拜香燃燒室中。

6、量測燃燒生成的總揮發性有機氣體、CO、CO_2等濃度

總揮發性有機氣體濃度之量測使用Mini-Rare 2000 (RAE SYSTEMS Inc., U.S.A.)。另外，設計小型稀釋腔導入拜香煙經過濾微粒，然後藉由高純度的氮氣將拜香燃燒所生的CO、CO_2稀釋，再使用Q-Trak^{TM} IAQ Monitor (Model 8550/8551, TSI Inc., U.S.A.) 量測，因為拜香燃燒所產生的CO、CO_2濃度高於儀器偵測上限。

7、量測燃燒生成的微粒粒徑分佈

使用包括靜電分徑儀（Electrostatic Classifier Model 3071A, TSI Inc., St. Paul, MN）和凝結核微粒計數器（Condensation Particle Counter Model 3025, TSI Inc., St. Paul, MN）兩個部分串接形成的 Scanning Mobility Particle Sizer (SMPS)，量測拜香燃燒所產生的微粒粒數濃度。SMPS 微粒粒徑量測範圍介於 17.2~1000 nm。

8、採樣分析微粒相上的有機化合物

針對拜香燃燒煙的微粒相進行採樣分析。採樣使用閉口式濾紙夾，搭配直徑 37 mm，含碳成分低，且較玻璃纖維濾紙不易吸附有機蒸氣之石英濾紙，採樣前，置入 900 ℃之高溫爐中烘烤八小時，去除濾紙上有機物質，待濾紙冷卻後保存於乾燥箱內(R.H.=45~50 %)，以備使用。採樣流量為 2 L/min，採樣流量藉由質量流量控制器控制，每次採樣前使用皂泡計進行校正。採樣時間為 10 min。

濾紙所採得的樣品使用二氯甲烷(CH_2Cl_2)進行溶劑萃取。處理程序包括：(1)萃取：將所採得之濾紙樣本分別置於 8 ml之棕色樣本瓶中，加入 5 ml的CH_2Cl_2，以鋁箔紙封住瓶口，置入超音波中，以超音波震盪 60 分鐘，取 1ml 萃取液置於 1.8 ml 茶色樣品中，並加入 2 ng (拜香A)或 20 ng (拜香B) 的Anthracene-D10 作為內標，避光貯存於-18℃，等待分析。使用氣相層析/質譜儀進行微粒相有機物種的定性與定量。氣相層析/質譜分析條件如下所示：(1)

毛細管柱：RTX RTX-5MS、I.D. 0.32 mm、length 60 m、film thickness 1.50 µm；(2)烘箱升溫梯度：保持 40 ℃初溫 1.5 分鐘，以每分鐘 10 ℃升溫速率加熱到 300 ℃，維持 300 ℃末溫 10 分鐘，總共 40.5 分鐘；(3)注射口溫度：300 ℃； (4)GC/MS介面溫度：32.00 ℃；質譜採用Scan mode掃描，掃描m/z範圍為 30-550；(5)載流氣體與流率：He，1.3 ml/min；(6)樣品注射體積：1 µl；(7)注射採非分流(splitless)方式。

9、採樣分析燃燒生成的氣相有機化合物

針對空氣中揮發性有機物(VOC)進行採樣，採用石英濾紙搭配活性碳吸附管，石英濾紙用以去除拜香燃燒所產生的微粒相物質，採樣流量率為 0.22 L/min，採樣時間為 15 min。

將吸附管前後段取出分別放到 1.8 ml 茶色樣品瓶中，加入 1 ml 二硫化碳，振盪 60 min，再加入 2 ng 的 ethyl benzene-d10 當作內標,隨即以氣相層析/質譜儀進行微粒相有機物種的定性與定量分析。所有樣本在採樣後一星期內分析完畢。氣相層析/質譜分析條件如下所示：分析管柱：Rtx- Volatile，60 m × 0.32 mm × 1.5 µm。載送氣體流量為 0.8 ml/min。升溫程式：40 ℃，8 分→5 ℃/min→220℃，10 min。注射口溫度：220℃。GC/MS 介面溫度：260℃。分流比 1.1。質譜儀操作模式為掃瞄模式（scan mode），掃瞄範圍在 25～300 之間，6.80 至 9.5 分時設定 MS detector off 以避免大量的萃取溶劑對儀器的傷害;ethyl benzene-d10 定量的離子 98。

10、有機化合物物種鑑別與定量

完整可靠的定性分析要使用每個物質的標準品，經由分析樣品比對由氣相層析分離得到滯留時間與由質譜得到的圖譜後才能確認。但在缺乏標準品的情況下，直接由氣相層析質譜進行有機物的定性分析，通常是使用內見的電腦軟體來協助判斷，由電腦內儲存的已知物質的質譜圖譜，經自動收尋的功能比對後將最可能的物質列出，並將比對用相似指數表示(match quality)。

為較準確的判定由拜香燃燒產生的有機污染物成分，本研究利用下列原則進行定性分析：(1)對所有在總離子強度明顯高於背景離子強度的波峰積分，然後先進行背景離子扣除步驟。(2)質譜圖譜與 library 比對結果高的相似性指數大於，仔細比較 Library 的圖譜與分析得到的圖譜，了解是否其中明顯含有其它的物質。(3)對於比對後相似性小於 80 的物質，利用 RIC 了解是否各波峰中含有兩種或兩種以上的物質。(4)針對(3)過程中判斷有其他物質存在造成複合質譜譜圖者，利用背景離子扣除的功能取得更具代表性的質譜譜圖。(5)利用 Library search 再次比對(4)得到的譜圖，以獲得新的 match quality。(6)由(5)中得到大於 80 的 match quality 者，在根據對質譜圖譜的解釋，來判斷比對的正確性。

一旦有機化合物被鑑別出來，每個鑑別出來的有機勿選取 2~4 各特定離子(Target Ion)作為往後定性的依據，並以 response 最大的特定離子作為定量離子，將個別有機化合物和內

標的定量離子的強度相對比值定義為相對強度因子(relative response factor)藉以量化有機化合物。

11、拍攝燃燒點特色

點燃的拜香置於內徑 2 cm、高度 15 cm 的透明玻璃圓管內，圓管外壁貼有刻度紙，用以記錄拜香燃燒點的高度，使用高階數位相機(COOLPIX995, NiKon, Japan)，調整適當的焦距，拍攝拜香燃燒點的燃燒狀態。

12、計算與數據處理分析

12-1 拜香燃燒速率的計算

拜香燃燒前與燃燒後重量差值除以燃燒時間即為燃燒速率。

12-2 氣態與微粒態污染物排放率與排放因子

依質量平衡原理氣態或微粒態污染物污染物排放率與排放因子是根據公式(1)導出：

$$V \times \frac{dCi}{dt} = R \times E_f - Q \times Ci \qquad (1)$$

式中V為測試腔體積(m^3)；C_i為氣態或微粒態污染物濃度(mg/m^3或$particles/cm^3$)；R為拜香燃燒速率(g/min)；E_f為氣態或微粒態污染物排放因子(mg/g或particles/g)；Q為氣體流量(0.005 m^3/min)。在拜香被點然後，拜香所產生的污染物濃度在短時間達到動態平衡，此時公式(1)中的 dCi/dt = 0，則(1)式可被改寫為下式：

$$E_f = \frac{Q \times C}{R} \qquad (2)$$

式中，C為測試腔內平衡時的氣態或微粒態的污染物濃度(mg/m^3或$particles/cm^3$)。如果上式應用於總揮發性有機化合物，因為總揮發性有機化合物(TVOCs)之量測，儀器讀出濃度以ppm表示，當轉換成mg/m^3時則假設總揮發性有機化合物的分子量為100 g。

三、結果與討論

1、拜香的元素組成與熱值

拜香A、B、C、D和E原料的熱值分別為3936、4619、4756、5060和4171Kcal/Kg。碳、氫、氮、灰燼及水份的組成分別為拜香A(檀香)的43.59、5.40、0.61、7.72和7.39 %；拜香B(無煙香)的55.24、3.96、0.57、10.30及6.16 %；拜香C(檜香)的53.38、4.71、0.51、12.55及9.56 %；拜香D的61.96、2.62、0.70和21.62 %；拜香E的48.4、4.93、0.79及40.42 %。另外，拜香D和E原物料的水份、揮發份、灰燼與固定碳分別為5.86、34.70、12.28與47.16 % 和8.94、54.4、4.74與31.92 %。此外，因拜香原物料揮發物含量的高低，將拜香D和E分別命名為低與高揮發物拜香。(表1)

2、流量率影響拜香燃燒點的溫度

拜香A點燃後維持在悶燒狀態，燃燒點之最高溫度隨流量率變化如圖2。

，在流量率在1 ~ 5 L/min時，最高溫度的溫度範圍為328.2 ℃ (n=3, CV=0.03) ~ 452.9 ℃ (n=3, CV＝0.02)；流量率介於10 ~ 20 L/min時，最高溫度的溫度範圍自253.0 ℃ (n=3, CV=0.04) 降到160.3 ℃ (n=3, CV＝0.06)。拜香燃燒速率(g/hr) 隨流量率逐漸升高直到流量率達15 L/min 而溫度為210.3 ℃ (n=3, CV=0.01) 之後，燃燒速率才緩勢下降，這種觀察與Wang (2003)等觀察海綿的燃燒速率和內部燃燒點溫度之關係略有不同，Wang氏等發現海綿內部達最高溫度時其燃燒速率最大，而本研究結果在流量率15 L/min時，拜香燃燒速率最高但表面溫度不是最高，可能高流量率冷卻熱偶式感測器造成溫度判讀之誤差。

3、含氧量改變燃燒點溫度與燃燒速率

固定流量率（5 L/min）下，空氣含氧量決定燃燒狀態（悶燒或有火焰燃燒）與燃燒點的溫度。當含氧量分別在19-45 %、18 -32.5 %的範圍變動時，A與B兩種拜香分別處於悶燒狀態，低於該範圍則熄滅，高於該範圍則轉成有火焰燃燒。悶燒時燃燒點溫度自400升到650℃，當溫度超過大約650℃時瞬即轉為有火焰燃燒，其溫度範圍760升到1200℃。燃燒速率隨著燃燒點溫度的升高成比例的增加。(圖3)在相同燃燒條件下，拜香B的燃燒速率與燃燒點溫度高於拜香A，可能因為拜香B原料熱值高於拜香A所造成。

4、拜香原物料及製成品粗細改變燃燒點的溫度與燃燒速率

固定流量率(5 L/min)下，正常空氣含氧量悶燒不同粗細的拜香D（無煙）與拜香E（有煙），三種粗細的無煙拜香(直徑為3、3.75和5 mm)，燃燒點皆成圓錐型，長度從13.5升到25 mm，三種粗細的有煙拜香(直徑為2.86、3.5和4.6 mm)，燃燒點亦成圓錐型，長度從4.5升到8 mm (圖4)，因為隨直徑的增加，拜香燃燒點的溫度亦隨之升高，則在燃燒底部

對於未進入燃燒狀態的部分拜香進行去除水分和熱分解亦加快，但在燃燒點上方隨直徑增加而延長燃燒時間，兩者促成隨直徑增加燃燒點的長度亦增長；此外，在約相同直徑下，拜香 D 燃燒點長度為拜香 E 的 3 倍長，也許因熱值和拜香原物料組成的密度不同所造成。另外，肉眼觀察兩種拜香燃燒點的亮度，隨著拜香的直徑增加而加亮，亦因為隨直徑的增加，拜香燃燒點的溫度隨之升高的關係。

悶燒三種細到粗的無煙拜香，平均溫度 (CV_{pooled}=0.03, n_{total}=3×3) 從 368 ℃ (n=3, CV=0.04) 升到 450 ℃ (n=3, CV=0.04)，燃燒速率 (CV_{pooled}=0.054, n_{total}=3×3) 從 1.67 g/hr (n=2, CV=0.02) 升到 3.3 g/hr (n=2, CV=0.07)；三種細到粗的有煙拜香，平均溫度 (CV_{pooled}=0.05, n_{total}=3×3) 從 242 ℃ (n=3, CV=0.04) 升到 336 ℃ (n=3, CV=0.03)，燃燒速率 (CV_{pooled}=0.06, n_{total}=3×3) 從 1.26 g/hr (n=3, CV=0.08) 升到 2.36 g/hr (n=3, CV=0.05)。這兩種分別由不同原料所製成的拜香，悶燒時的燃燒速率及燃燒點溫度皆隨拜香的直徑增加呈現比例的增加，這是因為隨拜香直徑的增加，燃燒點的表面積亦隨之增加，氧分子接觸燃燒點的機率亦增加，造成愈多的炭被氧化釋放出大量的熱，熱促成拜香燃燒速率的加快和表面溫度的升高。(圖 5)

5、微粒的排放特性

在正常大氣含氧下，悶燒拜香 A 產生的微粒大於拜香 B 與 C 所產生者，其微粒的數目粒徑中位數約為 200、80 和 100 nm (圖 6 與 7)。在相同的燃燒條件下悶燒拜香 A 產生的微粒大於拜香 B 及拜香 C 所產生者。

在悶燒拜香 A、B 與 C，隨氣體含氧量升高，燃燒點表面溫度升高，數目及體積粒徑中位數亦隨著變大，數目濃度及體積濃度亦增加，每克拜香所產生的體積排放因子增加，但數目排放因子不升反降 (圖 8 與 9)。以氣膠的觀點解釋，隨含氧量的增加，低揮發物濃度亦隨著增加，造成少部份的低揮發物發生同質成核作用產生新的小微粒，增加微粒的數目濃度，但大部份的低揮發物發生異質凝結作用(凝結在大微粒的表面積上)與微粒彼此亦會發生相膠作用共同促使微粒長大，此膠結作用會降低微粒的數目濃度。此外，在悶燒與火焰燃燒的狀況，質量濃度隨含氧量增加，質量排放因子亦呈現增加現象。在大氣含氧量為 20％的狀況下，燃燒拜香 A 所產生的微粒質量濃度排放率及排放因子分別為 33.4 mg/hr 與 29.0 mg/g。燃燒拜香 B 分別為 5.7 mg/hr 與 4.21 mg/g。燃燒拜香 C 分別為 13.5 mg/hr 與 16.0 mg/g (圖 10)。

Fine等(1999)在 0.64 m^3 容積系統中，研究在三種不同燃燒狀況下，燃燒一支蠟燭其所產生微粒之粒徑分佈，使用DMA連結CNC測量微粒直徑小於 200 nm其數目濃度，對於大粒徑範圍之微粒OPC進行測量，結果顯示(1)在”Normal burning”狀況下，燃燒蠟燭火焰小但穩定，無可見微粒產生，此時微粒質量排放率低且微粒直徑小於 100 nm；(2)在”Soot”狀況下，燃燒蠟燭有大而閃爍性火焰且有黑色可見微粒產生，此時高元素碳微粒排放；(3)

在"Smoldering"狀況下，出現在燃燒蠟燭火焰熄滅後時有白色可見微粒產生，此時微粒直徑在 400~800 nm。 Sooting flame 和smoldering wick蠟燭燃燒方式比normal burning燃燒方式會產生較高的細粒徑微粒排放率，藉由控制Sooting flame和smoldering wick蠟燭燃燒方式將可降低細粒徑微粒之排放，故作者等建議改變空氣氣流供給量和控制較好的蠟燭芯位置將可有效控制微粒之排放。

當拜香 A 與 B 從悶燒轉為火焰時，火焰燃燒所產生的微粒粒徑、數目、體積與質量排放率大於悶燒(圖 8)，可能因為此時火焰燃燒狀態為 Fine 等(1999)稱的 Sooting flame。另外，火焰燃燒拜香 C 時，當含氧量為 30 與 32.5 %時，火焰燃燒所產生的微粒粒徑、數目、體積與質量排放率皆低於悶燒最劇烈點(含氧量 27.5 %)，且隨含氧量的增加呈現下降趨勢，當含氧量為 35 %時，火焰燃燒所產生的微粒粒徑大於悶燒最劇烈點，且數目、體積與質量排放率轉為略微上升，可能因為火焰燃燒狀態從正常轉為 Sooting 的火焰燃燒(圖 9)。以氣膠的觀點解釋，在從悶燒轉為正常火焰時，隨著含氧量的增加，低揮發物濃度亦隨著減少，則同質成核作用形成新的小微粒降低，異質凝結作用亦降低，促使微粒粒徑變小，但當燃燒轉為 Sooting 火焰時，可能為拜香本身燃燒過於劇烈，促使有較大微粒排放。

綜合上述供給不同氧氣含量悶燒不同香種的微粒污染物的排放特性資料發現在低氧氣含量 20 %下，悶燒拜香會產生最低的微粒態(數目、體積和質量)污染物的排放率與排放因子

6、 CO、CO_2與TVOC等的排放與燃燒效率

悶燒拜香A與B時，氣相CO、CO_2與TVOC的濃度隨者供應氣體含氧量升高，檀香A 所產生的CO、CO_2濃度小於無煙拜香B所產生者，TVOC的產生則檀香A大於無煙拜香B。將濃度以拜香燃燒的克數歸一化成"排放因子"後，檀香A 所產生的CO、CO_2排放因子小於無煙拜香B所產生者，TVOC的排放則檀香A大於無煙拜香B。排放因子隨著供應氣體含氧量增加而變化， CO的排放因子上升， CO_2、TVOC的排放因子則緩勢下降。當達到火焰燃燒之際， CO、TVOC的濃度及排放因子迅速下降而且低於悶燒時之所見， CO_2則較特殊，除檀香A的排放因子下掉外其餘的濃度與排放因子均陡升。(圖 11 與 12)。

拜香從悶燒到有火焰燃燒時，燃燒效率範圍從 60~75 %轉到高於 90 %，當悶燒拜香時，檀香A與無煙拜香B的燃燒效率沒有隨著氣體含氧量的增加而有顯著的變化，兩種拜香的燃燒效率亦無顯著的差異。暗示悶燒拜香時其燃燒機制以熱烈解為主，有火焰時才真正的完全燃燒，促使CO氧化為CO_2和進一步的破壞有機化學物質(圖 13)。

7、氣流影響氣體和微粒的排放

當氣流流量率從 1 L/min 增加到 15 L/min時，拜香的燃燒速率隨流量率增加，因為隨氣流上升可增加氧分子傳輸到燃燒點表面，當流量率超過 15 L/min時，氣流有意義的帶走燃燒表面所產生的熱，燃燒速率逐漸下降。此時CO、CO_2、TVOC及微粒等的排放率與排放

因子的增加亦趨於平坦，但CO_2/(CO+CO_2)的比值反而下降，表示燃燒愈不完全。又隨著氣流的流量率上升微粒粒數及體積中位數粒徑有下降趨勢，因高流量率下快速稀釋高濃度微粒，致膠結效應減愈弱。總之，流量率為 1 L/min時，氣相和微粒相的排放率與排放因子最低，且燃燒效率愈完全。

8、拜香原物料萃取液的有機化學物種

A(檀香)、B(無煙香)與 C(檜香) **等**拜香**溶劑萃取液**分別被鑑定出 25、19 與 84 種有機化學物質。大量的是天然植物性香料貢獻的烷、烯、醇、酚、醛、酮類；拜香 C 可能含動物性香料 Musk(麝香)；拜香 A 與 C 含有 Camphene(樟腦精)；皆含有當作塑化劑的 Diethyl phthalate 和 Bis(2-ethylhexyl)phthalate。（表 2~3）

9、微粒相有機化合物的鑑定

表 4 與 5 鑑定悶燒與火焰燃燒拜香 A 與 C 所排放的微粒相有機化合物。悶燒燒拜香 A，質譜圖譜經由資料庫比對結果,相似性指數大於 80 的的微粒相有機污染物包括：(1) phenol 類 (2)Guaiacol 類 (3) Syringol 類 (4) PAH 類 (5)醛類(6)酯類，以及 (7). 2,3,5-Trimethoxytoluene。其中 2-methoxy-5-vinylphenol、4-hydroxy-3-methoxy-benzaldehyde、syringaldehyde、Bornyl cinnamate 2 和 Bis(2-ethylhexyl)phthalate 在原物料分析時已被鑑別出來。拜香 A 轉成火焰燃燒時，微粒相有機污染物果主要為碳數 21 到 29 的正烷類，可能係苯環類有機物裂解為高碳數的直鏈正烷類。

被稱為無煙拜香的 B，悶燒時，微粒相未發現任何的有機化合物，也許因為拜香的原料已經被經過熱處理且含有較高的熱值。

悶燒與火焰燃燒拜香 C，微粒相有機化合物包括：(1)烷類 (2).酚類 (3)Guaiacol 類 (4) Syringol 類 (5)PAH 類 (7)酯類 ，以及 2,3,5-Trimethoxytoluene、2-methyl-4-butyryl-phloroglucine 和 3-KETO-URS-12-ENE。除 2,3,5-Trimethoxytoluene、2-methyl-4-butyryl-phloroglucine 和 3-KETO-URS-12-ENE、sinapyl aldehyde 和 2,3,5-Trimethylnaphthalen 等五項有機化合物外，其餘各有機污染物被懷疑為存在原物料中的原形凝結在微粒表面，未經熱裂解，因為在原物料萃取液時皆已被鑑別出來。

悶燒拜香 C 所排放的酚、Guaiacol、Syringol、PAH 與醛類、2,3,5-Trimethoxytoluene、2-methyl-4-butyryl-phloroglucine 和 3-KETO-URS-12-ENE 等微粒相有機物，隨燃燒時含氧量的增加而上升，但轉為火焰時，上述的有機物迅速下降，因為被高溫破壞。另外，悶燒火焰燃燒拜香 C 所排放的微粒相低碳數烷類有機污染物，隨含氧量的增加，呈現下降的趨勢，因為低溫下產生較多量低碳數的烷類，隨溫度的升高，低碳數的烷類量的減少可能是被高溫進一步破壞。

Guaiacol 和 Syringol 類的同質衍生物主要來自於木質素的熱解，Furan 類的衍生物主要

來自於多醣體的熱解（Edye, et al, 1991)。另外，Ohlemiller, et al, (1995)發現悶燒燃料會產生比火焰燃燒燃料產生更多的毒性有機污染物。本研究燃燒拜香 A 與 C 的無火焰有機污染物釋放量相較於有火焰燃燒高和 Ohlemiller, et al, (1995)研究結果一致。

最後，若單一微粒相所含有機污染物對健康的影響，拜香 B 相較於拜香 A 與 B 可被視為較健康的拜香，因為有較低的微粒相有機污染物的釋放。

10、鑑定氣相揮發性有機污染物

表 6~8 鑑定悶燒與火焰燃燒拜香 A、B 與 C 所排放的氣相揮發性有機污染物。在悶燒拜香 A，鑑別十七種揮發性有機污染物屬於烷、烯、醛、酮、夫喃等類及苯環衍生物。當拜香燃燒轉為火焰時，僅存 1-propene 被發現。

在悶燒拜香 B，鑑別十種揮發性有機污染物屬於烷、烯、醛、酮、夫喃等類及苯環衍生物。當轉為火焰時，僅存 1-propene 與 toluene 被發現。

在悶燒拜香 C，鑑別二十三種揮發性有機污染物屬於烷、烯、醛、酮、夫喃等類及苯環衍生物外，尚包括 camphene, limonene, 與 camphor。當轉為火焰時，大部分有機揮發物依然存在，也許因為燃燒點溫度不夠高，無法將之進一步分解破壞。除 camphene, limonene, 與 camphor 可能為拜香原物料中存在的揮發物，其餘鑑別出的揮發性有機物為燃燒的真正產物。

此外，在上述鑑別出的 hexane, methyl-cyclopentane, 2,2-dimethyl-hexane, benzene 也存在活性碳吸附管中，在計算總揮發性有機物的量時有扣除背景值。

在悶燒 A、B 與 C 拜香階段，隨含氧量的增加，鑑別出的總揮發性有機化合物的相對強度因子皆呈現上升趨勢，相對強度因子範圍分別為 A(21.6~48.8)、B(6.12~10.55)與 C(9.99~20.67)。當拜香燃燒剛開始轉為火焰時，總揮發性有機化合物的相對強度因子隨之下降，相對強度因子分別為 A(0.05)、B(1.05)與 C(12.9)。另外，將上述結果和使用直讀式總有機碳分析結果互相比較，呈現一致性的趨勢。

四、結論與建議

無煙香原料含揮發份較低，有煙香原料含揮發份相對高，但後者熱值（kcal/g）略低。原物料熱值愈高，拜香轉為火焰燃燒的所需含氧量越低，但無論何種拜香，當溫度超過大約650 ℃時瞬即轉為有火焰燃燒，之前悶燒的溫度介於自 400 升到 650 ℃。當拜香悶燒時，在相同的環境因素（空氣含氧量及流量率）下，高熱值拜香的燃燒點表面溫度較高，粗的拜香燃燒點表面溫度亦較高；燃燒點溫度，也會分別隨著補充空氣的含氧量與流量率的增加而升高，但流量率超過 15 L/min時開始有明顯的冷卻至溫度持恆（約 210℃）的效應。同一種拜香當燃燒點溫度升高時，燃燒率以及CO、CO_2、TVOCs及微粒的排放率與排放因子亦遞升，燃燒率以及氣體及微粒的排放率之自然對數值分別與燃燒點絕對溫度的倒數成良好的線性關係；至於兩種拜香比較，無煙香原料含揮發份較低，熱值（kcal/g）相對高，燃燒點表面溫度亦較高，CO、CO_2的排放因子（mg/g）相對的高，TVOCs排放因子相對的低，產生較低的微粒濃度（質量濃度與粒數濃度），而粒徑中位數亦相對的較小。至於同種拜香，粗的產生較多的粒數濃度，而且同種拜香在流率為 15 L/min以下時，隨著流率增加粒徑變小而數目增加，但無論如何粒徑份佈均在次微米下。

未經燃燒的 A(檀香)、B(無煙香)與 C(檜香) 等拜香溶劑萃取液分別被鑑定出 25、19 與 84 種有機化學物質。大量的是天然植物性香料貢獻的烷、烯、醇、酚、醛、酮及酯類，亦含少量可能是由動物性香料貢獻的如出現於拜香 C 之麝香 (musk)。當作塑化劑用的 diethyl phthalate 和 bis(2-ethylhexyl)phthalate 也出現在拜香的溶劑萃取液。拜香燃燒所產生的微粒相有機污染物，部分源自於原物料中的原形（低揮發性有機物）蒸發後再凝結在微粒表面，部分為真正燃燒的產物。悶燒拜香所產生微粒相高碳分子量有機物，隨燃燒時含氧量的增加而上升，但轉為火焰時，被高溫破壞而迅速下降。另外，悶燒拜香低碳數烷類有機污染物，隨含氧量的增加，呈現下降的趨勢，因為低溫下產生較多量低碳數的烷類，隨溫度的升高，低碳數的烷類量的減少可能是被高溫進一步破壞。在氣相所見的有機揮發物，其狀況亦十分相近。

含揮發份較低，熱值（kcal/g）高的無煙香或稱環保香， TVOCs 排放因子相對的低，產生較低的微粒濃度（質量濃度與粒數濃度），對於污染的預防似乎是正面的，但是粒徑中位數亦相對的較小，小於 1 µm 的微粒，甚至產生小於 100 nm 的超細粒徑微粒，可能因粒數增加、粒徑縮小至整體表面積提生，可以負載著較多的有害物，改變了微粒物理和化學特性而提升微粒的生物毒性(氧化壓力和發炎反應)亦未可知，故未來需要對拜香燃燒所產生的細微粒進行細胞毒理學的探討。

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六、已發表及擬發表之著作

1. Tzu-Ting Yang[1], Chih-Chieh Chen[2] and Jia-Ming Lin*, Effect of air flow on emission of smoldering incense. Bulletin of Environmental Contamination and Toxicology 74: 456-463(2005)
2. Tzu-Ting Yang[1], Jia-Ming Lin[2] and Chih-Chieh Chen*, Characterization of aerosol emission from smoldering incenses. (Submitted to Journal of Aerosol Science and Technology, in revision)
3. Tzu-Ting Yang, Ming-Heng Huang,Yee-Chung Ma**,** Jia-Ming Lin*, Characterization of organic compounds in gas phase and particulate phase from smoldering and flaming incense. (In preparation)

Table 1. Compositions and heating values of incenses A、B、C and D

Element	Incense				
	A	B	C	D	E
C	43.59	55.24	53.38	61.96	48.4
H	5.40	3.96	4.71	2.62	4.93
N	0.61	0.57	0.51	0.70	0.79
O	39.61	28.82	28.75	21.62	40.42

Unit is %

Composition	Incense				
	A	B	C	D	E
Water	7.39	6.16	9.56	5.86	8.94
Volatile	75.8	49.79	27.84	34.7	54.4
Ash	7.15	10.53	11.35	12.28	4.74
Fix. Carbon	9.66	33.52	51.25	47.16	31.92
Heatig value (Kcal/Kg)	3936	4619	4756	5060	4171

Unit is %

Table 2 Identification and Quantification of the organic compounds from the material of incense A and B

	Target Compound of incense A	R.R.F		Target Compound of incense B	R.R.F
1	2-Cyclohexen-1-one	6.44	1	2-Cyclohexen-1-one	0.06
2	Camphene	3.72	2	Menthone	0.01
3	Benzaldehyde	3.88	3	Dodecane	0.01
4	Camphor	2.78	4	ANETHOLE	0.02
5	Dodecane	1.29	5	Tridecane	0.03
6	berbenone	1.00	6	EUGENOL	0.52
7	Tridecane	2.80	7	anethole	1.00
8	2-Methoxy-5-vinylphenol	1.74	8	2,3-dihydro-1H-Inden-1-one	0.03
9	Tetradecane	2.58	9	Tetradecane	0.02
10	4-hydroxy-3-methoxy-Benzaldehyde	0.78	10	4-hydroxy-3-methoxy-Benzaldehyde	0.02
11	Pentadecane	1.38	11	.alpha.-CEDRENE	0.07
12	Hexadecane	1.27	12	WIDDRENE	0.02
13	Diethyl phthalate	9.02	13	alpha-curcumene	0.02
14	Syringaldehyde	1.42	14	Pentadecane	0.01
15	Benzyl benzoate	1.03	15	(+)-CUPARENE	0.03
16	Docosane(C22H46)	0.92	16	Hexadecane	0.01
17	Bornyl cinnamate 2	128.72	17	Diethyl phthalate	0.07
18	Tricosane(C23H48)	1.68	18	Cedrol	0.18
19	Tetracosane(C24H50)	1.95	19	Bis(2-ethyhexyl)phthalate)	0.05
20	Pentacosane(C25H52)	2.38			
21	Bis(2-ethyhexyl)phthalate)	19.09			
22	Hexacosane(C26H54)	2.58			
23	Heptacosane(C27H56)	2.77			
24	Octacosane(C28H58)	2.03			
25	HINOKININ	53.56			
	Anthracene-d10*	1.00			

* Internal standard

R.R.F is relative response factor

Table 3 Identification and Quantification of the organic compounds from the material of incense C

	Target Compound of incense C	RSD		Target Compound of incense C	R.R.F		Target Compound of incense C	R.R.F
1	SANTENE	0.03	31	ANETHOLE	0.01	61	gamma.-Cadinene	0.82
2	tricyclene	0.07	32	berbenone	0.02	62	.delta.-cadinene	0.26
3	thujene	7.28	33	Linalyl acetate	0.24	63	Phenylphenol	1.76
4	.ALPHA.-PINENE	8.01	34	E-Citral	0.24	64	.ALPHA.-CALACORENE	0.25
5	2-Cyclohexen-1-one	0.26	35	dl-Limonene	0.07	65	Hexadecane	0.03
6	Camphene	1.00	36	bornyl acetate	0.98	66	Diethyl phthalate	0.10
7	verbenene	0.03	37	ISOBORNYL ACETATE	0.90	67	(-)-Caryophyllene oxide	0.16
8	Benzaldehyde	0.01	38	Tridecane	0.05	68	Cedrol	1.91
9	cymene	0.08	39	EUGENOL	0.11	69	Syringaldehyde	0.02
10	beta.-PINENE	2.76	40	anethole	0.02	70	Benzyl benzoate	1.12
11	MYRCENE	0.15	41	2,3-dihydro-1H-Inden-1-one	0.01	71	2-methyl-4-butyryl-phloroglucine	0.09
12	l-Phellandrene	0.11	42	2-Methoxy-5-vinylphenol	0.02	72	Chlorothalonil	0.36
13	.DELTA.-3-CARENE	0.21	43	.Alpha.-Terpinene	0.86	73	musk	0.16
14	cymene	2.74	44	2,6-dimethoxy-Phenol	0.01	74	Heneicosane(C21H44)	0.01
15	LIMONENE	2.72	45	.ALPHA.-COPAENE	0.27	75	Docosane(C22H46)	0.01
16	TRANS-.BETA.-OCIMENE	0.01	46	Tetradecane	0.04	76	Tricosane(C23H48)	0.01
17	dihydromyrcenol	0.08	47	beta.-elemene	0.11	77	dehydroabietic acid	0.46
18	CIS-LINALOOL OXIDE	0.04	48	4-hydroxy-3-methoxy-Benzaldehyde	0.33	78	Tetracosane(C24H50)	0.01
19	dehydro-cymene	0.18	49	Cyperene	0.63	79	Pentacosane(C25H52)	0.01
20	LINALOOLL	3.85	50	alpha.-Gurjunene	0.39	80	Bis(2-ethyhexyl)phthalate)	0.04
21	methyl-Phenol	0.01	51	.alpha.-CEDRENE	4.00	81	Hexacosane(C26H54)	0.01
22	NEO-ALLO-OCIMENE	0.09	52	BETA.-CARYOPHYLLENE	0.84	82	Heptacosane(C27H56)	0.01
23	TERPINENE 1-OL	0.23	53	GAMMA.-MUUROLENE	0.75	83	Octacosane(C28H58)	0.01
24	beta-terpineol	0.29	54	WIDDRENE	2.63	84	3-KETO-URS-12-ENE	0.66
25	Camphor	2.80	55	.ALPHA.-HUMULENE	0.43		Anthracene-d10*	1.00
26	Menthone	0.58	56	alpha-curcumene	0.11			
27	MENTHONE	0.24	57	Pentadecane	0.04			
28	4-terpijneol	0.58	58	ACETOVANILLONE	0.01			
29	Dodecane	0.02	59	alpha.-Muurolene	0.40			
30	.ALPHA-TERPINEOL	4.67	60	(+)-CUPARENE	1.13			

* Internal standard

R.R.F is relative response factor

Table 4 Identification and Quantification of the organic compounds of particulate matter using GC/MS from burning incense A

Target Compound	R.T.	Q-Ion	Q-value	20% (n=4)	S.D.**	30% (n=4)	S.D.	40% (n=5)	S.D.	45% (n=1)
Anthracene-D10 *	20.81	**188**,94,160,189	94	1.00	0.00	1.00	0.00	1.00	0.00	N.D.
methyl-Phenol	11.08	**108**,107,79	80	N.D.***	N.D.	0.04	0.02	0.10	0.02	N.D.
methyl-Phenol	11.42	**108**,107,80	80	N.D.	N.D.	0.24	0.09	0.52	0.14	N.D.
methoxy-Phenol	11.61	**124**,109,91	81	N.D.	N.D.	0.11	0.05	0.17	0.10	N.D.
4-vinylphenol	13.53	**120**,91,39	87	0.17	0.12	2.85	1.25	3.14	0.91	N.D.
cinnamic aldehyde	13.67	**131**,103,78	82	0.07	0.01	0.25	0.04	0.37	0.06	N.D.
1-INDANONE	14.57	**132**,104,78	90	0.06	0.02	0.17	0.05	0.25	0.06	N.D.
2-Methoxy-5-vinylphenol	14.92	**150**,135,107,77	87	0.32	0.05	1.82	0.40	1.84	0.43	N.D.
2-Methylindanone	15.06	146, **131**, 117	80	0.00	N.D.	0.06	0.02	0.09	0.02	N.D.
2,6-dimethoxy-Phenol	15.41	**154**, 139, 111	95	1.23	0.12	3.99	0.86	3.38	0.74	N.D.
4-hydroxy-3-methoxy-Benzaldehyde	16.17	152, **151**, 123	90	0.10	0.10	0.83	0.14	0.97	0.19	N.D.
EUGENOL	16.19	**164**, 149, 131	93	0.04	0.04	0.25	0.05	0.24	0.06	N.D.
ACETOVANILLONE	17.28	**151**, 123	90	0.03	0.05	0.47	0.08	0.48	0.07	N.D.
2,3,5-Trimethoxytoluene	17.64	182, **167**	86	0.53	0.05	0.98	0.17	0.77	0.16	N.D.
Methoxyeugenol	18.56	**194**, 119, 91	87	0.18	0.01	0.49	0.09	0.45	0.10	N.D.
Methoxyeugenol	19.14	**194**, 119, 91	87	0.14	0.02	0.35	0.07	0.26	0.07	N.D.
Syringaldehyde	19.32	**182**, 181, 167	91	0.08	0.09	0.87	0.16	0.96	0.21	N.D.
Methoxyeugenol	19.69	**194**, 119, 91	94	0.68	0.03	1.52	0.34	1.15	0.33	N.D.
3-(3',5'-dimethoxy-4'-hydroxyphenyl)-E-2-propenal	22.71	**208**, 165, 137	80	N.D.	N.D.	N.D.	N.D.	0.03	0.07	N.D.
Bornyl cinnamate 2	24.91	284, **131**, 109	93	0.22	0.05	0.45	0.04	0.51	0.10	N.D.
Bis(2-ethylhexyl)phthalate	27.33	279, 167, **149**	80	0.07	0.05	0.11	0.01	0.13	0.02	N.D.
Docosane	24.55	**57**, 43	96	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.02
Tricosane	25.38	**57**, 43	95	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.07
Tetracosane	26.23	**57**, 43	94	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.12
Pentacosane	27.02	**57**, 43	91	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.18
Hexacosane	27.77	**57**, 43	99	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.18
Heptacosane	28.56	**57**, 43	98	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.17
Octocosane	29.40	**57**, 43	97	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.11

* Internal standard
** Standard deviation
*** N.D. not determined, possible at low level

Table 5 Identification and quantification of the organic compounds of particulate matter using GC/MS from burning incense C

Target Compound	20% (n=3)	S.D.**	22.5% (n=3)	S.D.	25% (n=3)	S.D.	27.5% (n=3)	S.D.	30% (n=3)	S.D.
Dodecane	0.075	0.000	0.066	0.009	0.028	0.003	0.027	0.005	0.027	0.001
Tridecane	0.172	0.004	0.143	0.026	0.064	0.006	0.061	0.009	0.057	0.001
2-Methoxy-5-vinylphenol	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.010	0.000	0.000
2,6-dimethoxy-Phenol	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.008	0.000	0.000
Tetradecane	0.146	0.005	0.120	0.021	0.055	0.007	0.052	0.009	0.049	0.003
Pentadecane	0.066	0.001	0.055	0.010	0.025	0.001	0.025	0.004	0.022	0.001
ACETOVANILLONE	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.009	0.000	0.000
Phenylphenol	0.009	0.013	0.057	0.018	0.082	0.002	0.141	0.029	0.080	0.012
2,3,5-Trimethoxytoluene	0.000	0.000	0.019	0.001	0.022	0.001	0.038	0.006	0.018	0.003
2,3,5-TRIMETHYLNAPHTHALEN	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.009	0.000	0.000
Hexadecane	0.054	0.000	0.044	0.008	0.020	0.002	0.020	0.003	0.018	0.000
Diethyl phthalate	2.870	0.157	2.028	0.366	0.182	0.005	0.150	0.020	0.122	0.010
Methoxyeugenol	0.000	0.000	0.000	0.000	0.000	0.000	0.021	0.003	0.000	0.000
Syringaldehyde	0.000	0	0.022	0.003	0.031	0.001	0.058	0.004	0.060	0.010
Methoxyeugenol	0.040	0.004	0.065	0.005	0.075	0.002	0.113	0.009	0.019	0.003
Benzyl benzoate	0.000	0.000	0.024	0.003	0.031	0.001	0.050	0.006	0.029	0.003
2-methyl-4-butyryl-phloroglucine	0.041	0.010	0.060	0.005	0.063	0.003	0.101	0.003	0.061	0.007
$C_{11}H_{12}O_4$	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.008	0.000	0.000
Tetracosane($C_{24}H_{50}$)	0.044	0.006	0.028	0.006	0.000	0.000	0.000	0.000	0.000	0.000
Bis(2-ethyhexyl)phthalate)	0.152	0.020	0.154	0.010	0.064	0.019	0.073	0.036	0.103	0.023
Octacosane($C_{28}H_{58}$)	0.000	0.000	0.006	0.010	0.000	0.000	0.000	0.000	0.000	0.000
3-KETO-URS-12-ENE	0.000	0.000	0.000	0.000	0.025	0.035	0.063	0.006	0.034	0.004

Internal standard is Anthracene-D10

** Standard deviation

*** 0. not determined, possible at low level

Table 6 Identification and quantification of the volatile organic compounds from burning incense A

Target Compound	Q-Ion	R.T.	20% (n=3)		25% (n=3)		30% (n=3)		40% (n=3)		45% (n=1)	
			AVG	SD**	AVG	SD	AVG	SD	AVG	SD	AVG	SD
ethylbenzene-d10*			1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
1-Propene	**41**,39	4.5	5.57	0.97	8.48	0.65	7.07	0.43	9.43	2.13	0.05	0.05
1,2-Propadiene	**40**,39	4.8	1.29	0.21	1.74	0.23	1.94	0.11	3.36	0.81	0.00	0.00
2-methyl-1-Propene	**41**,56,55	5.3	2.25	0.41	2.98	0.25	2.86	0.26	4.04	0.93	0.00	0.00
1,3-Butadiene	**54**,53,39	5.5	1.42	0.43	2.60	0.23	2.07	0.05	3.34	0.74	0.00	0.00
acetaldehyde	**44**,29	5.6	2.17	0.27	2.96	0.49	4.16	0.43	7.10	2.16	0.00	0.00
furan	**68**,39	8.1	2.13	0.33	2.37	0.21	2.34	0.19	3.41	0.75	0.00	0.00
acetone	**43**,58	8.3	2.09	0.29	2.89	0.41	3.55	0.37	5.32	1.37	0.00	0.00
acetonitrile	**41**,40	8.9	0.70	0.10	0.94	0.12	0.99	0.10	1.59	0.41	0.00	0.00
Hexane	**57**,86,56	11.8	9.41	59.45	52.27	11.30	190.78	363.08	10.90	74.43	83.09	78.68
methyl-cyclopentane	**56**,69,84	14.0	0.05	0.63	0.00	0.16	3.12	6.35	-0.24	0.70	0.51	0.72
2,2-dimethyl-hexane	**57**,56,99	16.6	-0.03	0.07	-0.05	0.02	0.37	0.78	-0.35	0.64	0.04	0.07
Benzene	**78**,77	17.0	5.41	2.46	13.37	2.48	13.28	2.32	20.49	2.87	0.44	0.21
toluene	**91**,92	22.4	2.95	1.16	4.74	0.62	4.18	0.41	6.71	0.92	0.00	0.00
furaldehyde	**96**,95,39	26.6	0.00	0.00	0.00	0.00	0.33	0.08	0.62	0.10	0.00	0.00
ethylbenzene	**91**,106	26.8	0.24	0.42	0.84	0.10	0.89	0.09	1.45	0.15	0.00	0.00
xylene	**91**,106	27.2	0.24	0.42	0.71	0.05	0.67	0.07	0.99	0.14	0.00	0.00
styrene	**104**,78	28.3	0.02	0.03	0.84	0.17	0.79	0.14	1.48	0.20	0.00	0.00
Total Target Compound			21.06		32.10		31.82		48.84		0.05	

* Internal standard

** Standard deviation

0.00 Not determined, possible at low level

Table 7 Identification and Quantification of the volatile organic compounds from burning incense B

Target Compound	Q-Ion	R.T.	20% (n=3)		25% (n=3)		30% (n=3)		32.5% (n=3)		35% (n=3)		40% (n=3)	
			AVG	SD**	AVG	SD	AVG	SD	AVG	SD	AVG	SD	AVG	SD
ethylbenzene-d10*			1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
1-Propene	**41**,39	4.5	2.79	0.42	3.23	0.66	4.07	0.77	0.79	1.07	0.00	0.00	0.00	0.00
1,2-Propadiene	**40**,39	4.8	0.00	0.00	0.15	0.25	0.75	0.15	0.00	0.00	0.00	0.00	0.00	0.00
2-methyl-1-Propene	**41**,56,55	5.3	0.58	0.09	0.66	0.12	0.85	0.14	0.00	0.00	0.00	0.00	0.00	0.00
1,3-Butadiene	**54**,53,39	5.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
acetaldehyde	**44**,29	5.6	0.35	0.31	0.62	0.10	1.06	0.22	0.00	0.00	0.00	0.00	0.00	0.00
isoprene	**53**,67,27	8.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
furan	**68**,39	8.1	0.64	0.10	0.69	0.11	0.83	0.10	0.00	0.00	0.00	0.00	0.00	0.00
acetone	**43**,58	8.3	0.38	0.35	0.68	0.08	1.00	0.13	0.15	0.30	0.00	0.00	0.00	0.00
acetonitrile	**41**,40	8.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hexane	**57**,86,56	11.8	-101.90	38.52	-104.83	72.58	-70.41	76.31	26.15	115.96	-164.58	73.29	-65.19	246.38
methyl-cyclopentane	**56**,69,84	14.0	-1.83	0.95	-2.54	0.49	-1.30	1.23	0.94	1.75	-1.39	1.22	-0.64	3.52
2,2-dimethyl-hexane	**57**,56,99	16.6	-0.25	0.08	-0.34	0.05	-0.21	0.11	0.08	0.15	-0.16	0.10	-0.08	0.31
Benzene	**78**,77	17.0	4.55	0.93	7.39	2.33	6.88	0.09	1.89	1.04	-0.63	0.58	-0.19	1.68
toluene	**91**,92	22.4	1.38	0.24	1.91	0.69	1.99	0.21	0.11	0.18	-0.46	0.09	-0.42	0.16
furaldehyde	**96**,95,39	26.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ethylbenzene	**91**,106	26.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
xylene	**91**,106	27.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
dimethyl benzene	**91**,106,105	28.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
styrene	**104**,78	28.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
alpha-pinene	**93**,136,77	29.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Camphene	**93**,121,136	30.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
limonene	**68**,93,136	33.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
isopropyltoluene	**119**,134,91	33.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
isopropenyltoluene	**132**,117,91	35.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
camphor	**95**,152,81	38.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Target Compound			6.12		7.93		10.55		1.05		0.00		0.00	

* Internal standard

** Standard deviation

0.00 Not determined, possible at low level

Table 8 Identification and Quantification of the volatile organic compounds from burning incense C

Target Compound	Q-Ion	R.T.	20% (n=3)		22.5% (n=3)		25% (n=3)		27.5% (n=3)		30% (n=3)	
			AVG	SD**	AVG	SD	AVG	SD	AVG	SD	AVG	SD
ethylbenzene-d10*			1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
1-Propene	**41**,39	4.5	1.85	0.09	2.10	0.06	3.47	0.28	3.05	0.41	2.29	0.41
1,2-Propadiene	**40**,39	4.8	0.00	0.00	0.19	0.16	0.57	0.03	0.54	0.07	0.51	0.08
2-methyl-1-Propene	**41**,56,55	5.3	0.74	0.02	0.84	0.02	1.34	0.10	1.18	0.14	0.91	0.15
1,3-Butadiene	**54**,53,39	5.5	0.00	0.00	0.10	0.17	0.71	0.06	0.61	0.08	0.31	0.28
acetaldehyde	**44**,29	5.6	0.57	0.03	0.58	0.01	1.06	0.07	0.93	0.11	0.99	0.09
isoprene	**53**,67,27	8.1	0.00	0.00	0.19	0.16	0.67	0.04	0.55	0.06	0.25	0.23
furan	**68**,39	8.1	0.90	0.05	0.95	0.05	1.61	0.12	1.38	0.16	0.66	0.59
acetone	**43**,58	8.3	0.93	0.02	1.01	0.05	1.51	0.13	1.38	0.13	1.36	0.13
acetonitrile	**41**,40	8.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hexane	**57**,86,56	11.8	-444.29	2.75	-448.62	12.35	-447.28	5.54	-454.88	9.64	-438.50	4.44
methyl-cyclopentane	**56**,69,84	14.0	-11.09	0.03	-11.13	0.10	-11.15	0.05	-11.16	0.07	-11.05	0.06
2,2-dimethyl-hexane	**57**,56,99	16.6	-1.59	0.00	-1.59	0.00	-1.59	0.00	-1.59	0.00	-1.59	0.00
Benzene	**78**,77	17.0	-1.66	0.31	-1.22	0.70	0.13	0.57	0.46	0.58	-0.02	0.37
toluene	**91**,92	22.4	0.82	0.12	1.42	0.23	2.48	0.41	2.89	0.25	1.62	0.48
furaldehyde	**96**,95,39	26.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ethylbenzene	**91**,106	26.8	0.00	0.00	0.00	0.00	0.48	0.56	0.34	0.03	0.11	0.19
xylene	**91**,106	27.2	0.52	0.07	0.69	0.02	1.03	0.13	1.12	0.02	0.66	0.13
dimethyl benzene	**91**,106,105	28.3	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.16	0.00	0.00
styrene	**104**,78	28.3	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.15	0.00	0.00
alpha-pinene	**93**,136,77	29.3	0.72	0.02	0.75	0.07	0.92	0.10	0.96	0.02	0.63	0.08
Camphene	**93**,121,136	30.2	0.10	0.17	0.19	0.17	0.39	0.03	0.39	0.01	0.00	0.00
limonene	**68**,93,136	33.1	0.67	0.05	0.77	0.05	1.03	0.06	1.06	0.04	0.61	0.11
isopropyltoluene	**119**,134,91	33.2	2.17	0.11	2.44	0.07	3.24	0.28	3.24	0.08	1.98	0.33
isopropenyltoluene	**132**,117,91	35.8	0.00	0.00	0.10	0.17	0.48	0.05	0.50	0.04	0.00	0.00
camphor	**95**,152,81	38.6	0.00	0.00	0.00	0.00	0.34	0.03	0.28	0.24	0.00	0.00
Total Target Compound			9.99		12.34		21.32		20.67		12.90	

* Internal standard

** Standard deviation

0.00 Not determined, possible at low level

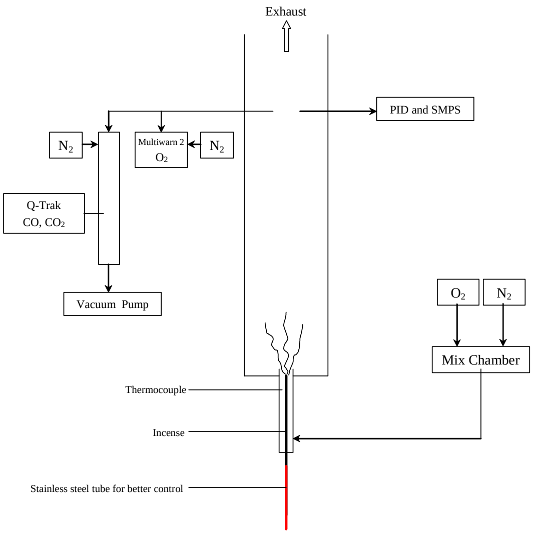


Figure 1 Schematic diagram of incense combustion system set-up in various oxygen fractions

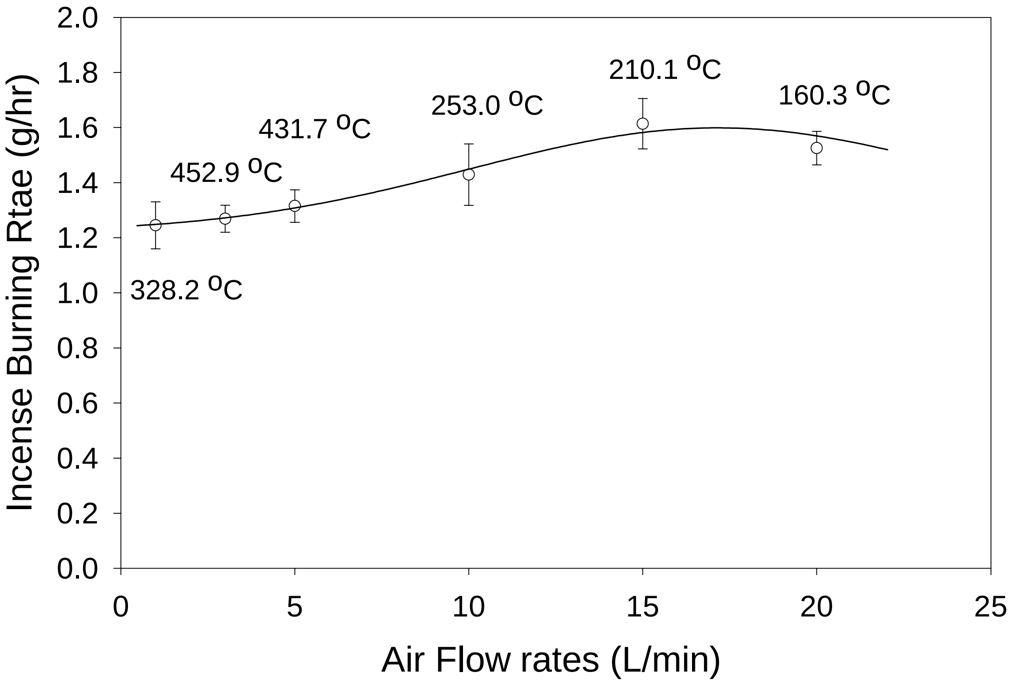


Figure 2. Burning rate and maximum temperature of burning tip at various air flow rates (Bar: mean ± standard deviation).

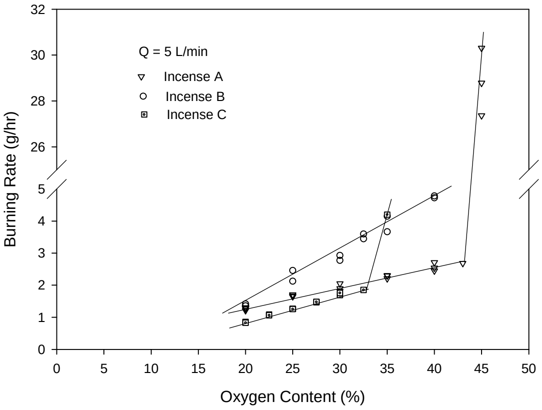
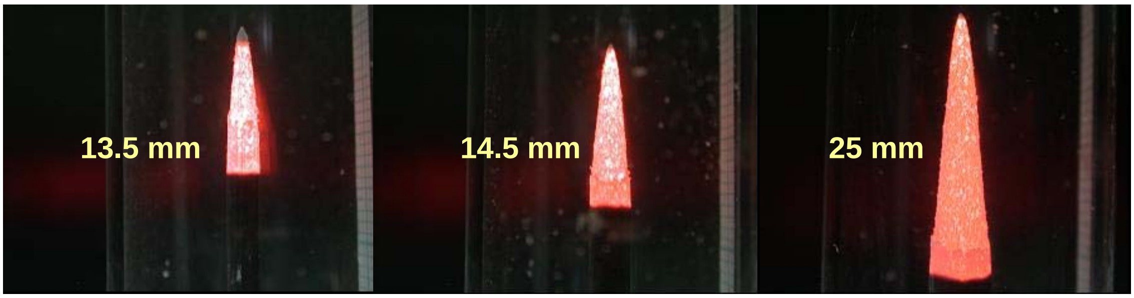
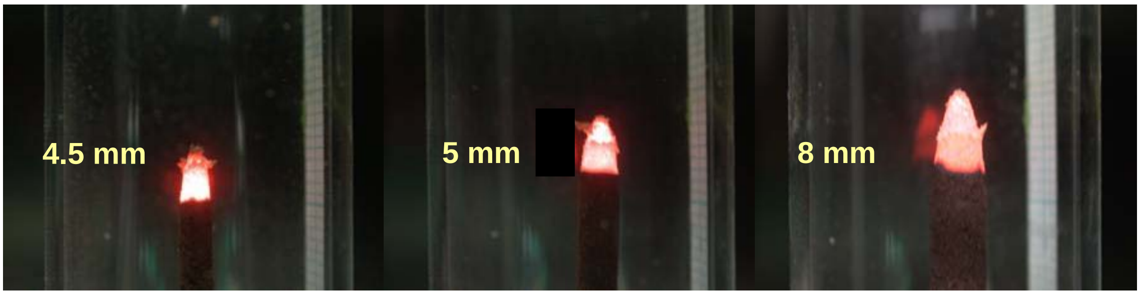


Figure 3 Comparison of burning rates of incenses A、B and C



Diameter 3 mm 3.75 mm 5 mm

Low Volatility Incense



Diameter 2.86 mm 3.5 mm 4.6 mm

High Volatility Incense

Figure 4. Profiles of burning fire cones of incenses with various diameters and compositions of volatile component

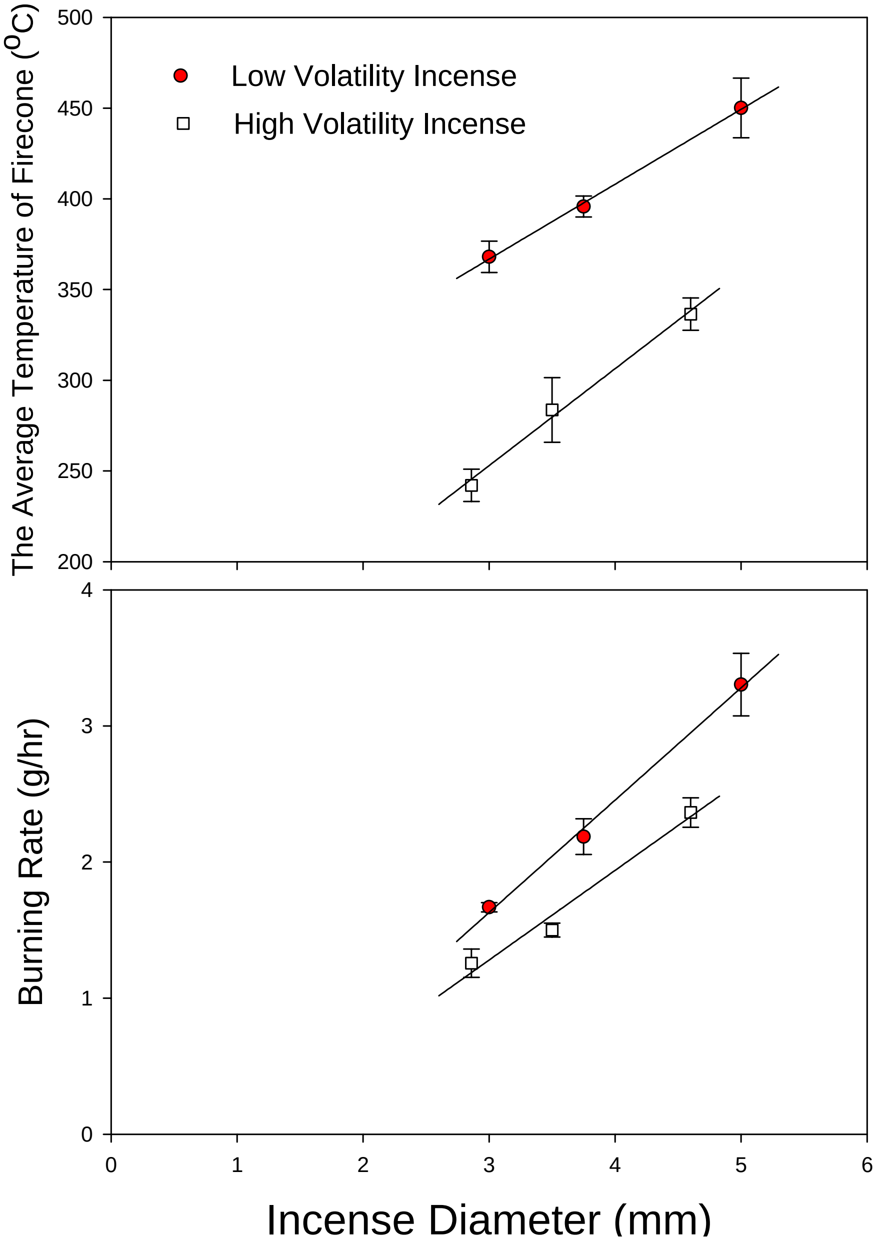


Figure 5. Change of burning rate along with type of incense, its diameter and temperature at the burning tip in smoldering condition.

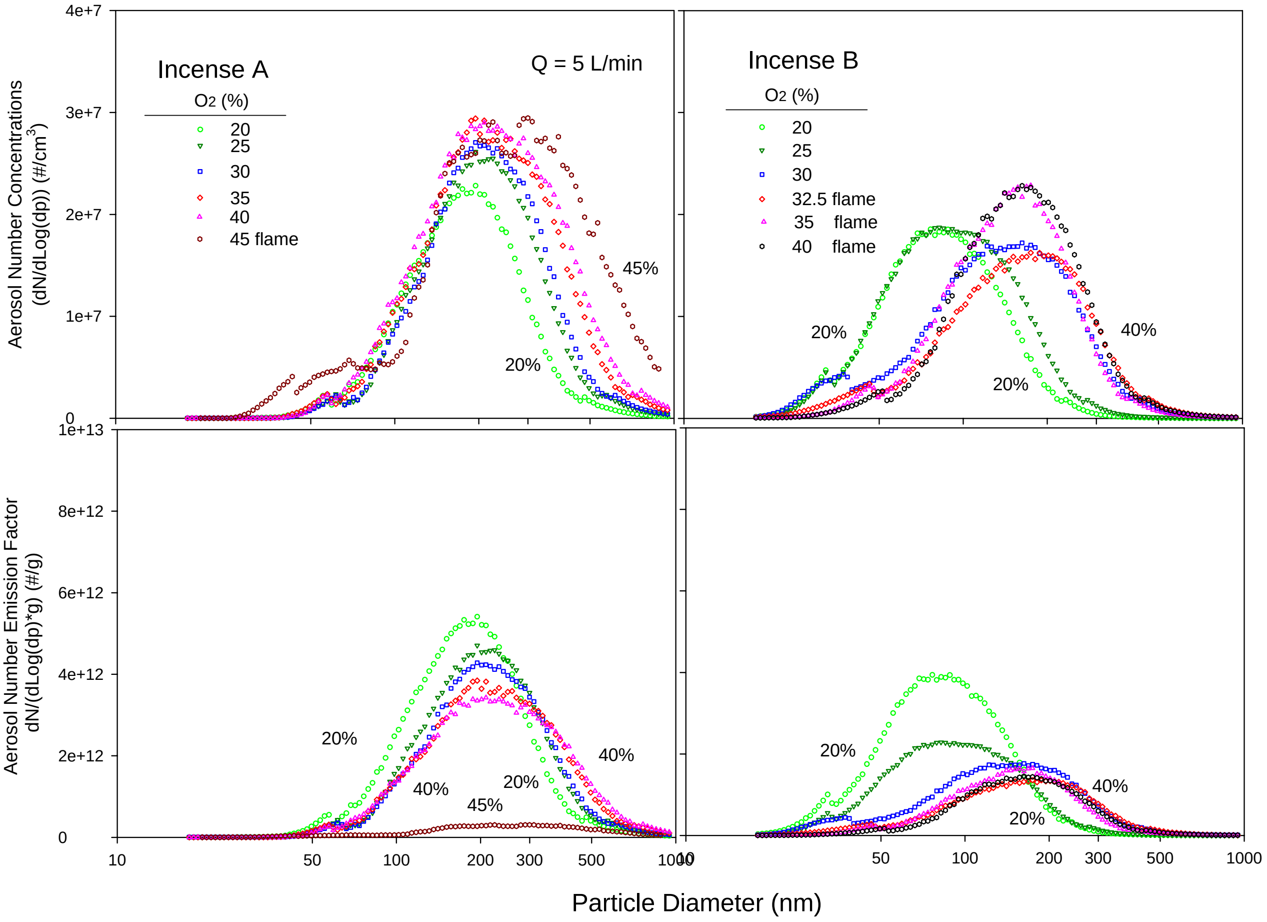


Figure 6. Aerosol number concentrations, emission rates and factors versus size of particles from burning the incenses A and B at various oxygen contents while the supplied air flow rate was kept at 5 L/min.

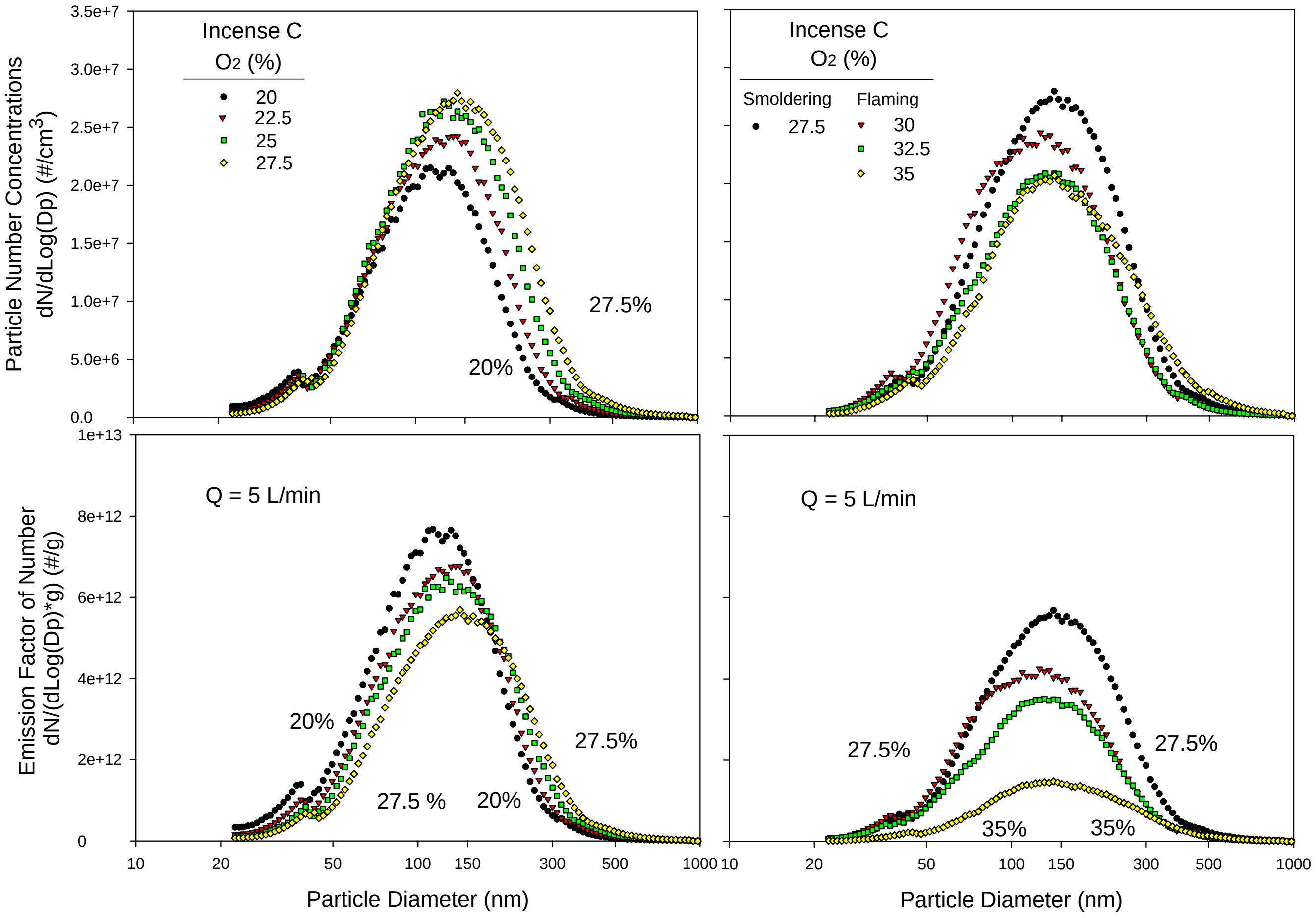


Figure 7. Aerosol number concentrations, emission rates and factors versus size of particles from the burning incense C at various oxygen contents while the supplied air flow rate was kept at 5 L/min.

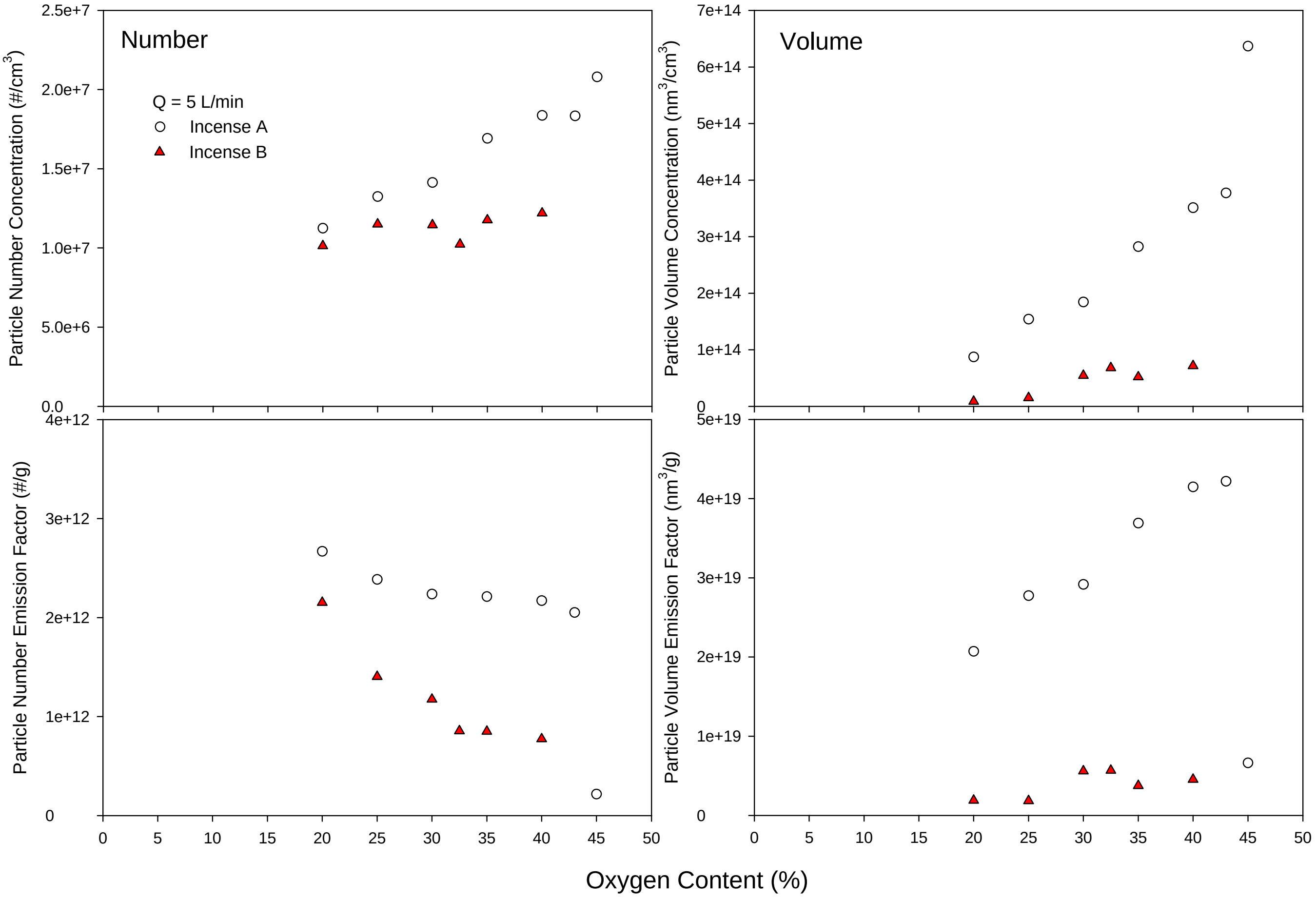


Figure 8. Submicron aerosol number and mass concentrations and their corresponding emission rates and factors versus oxygen contents at air flow rate of 5L/min for burning incenses A and B, respectively

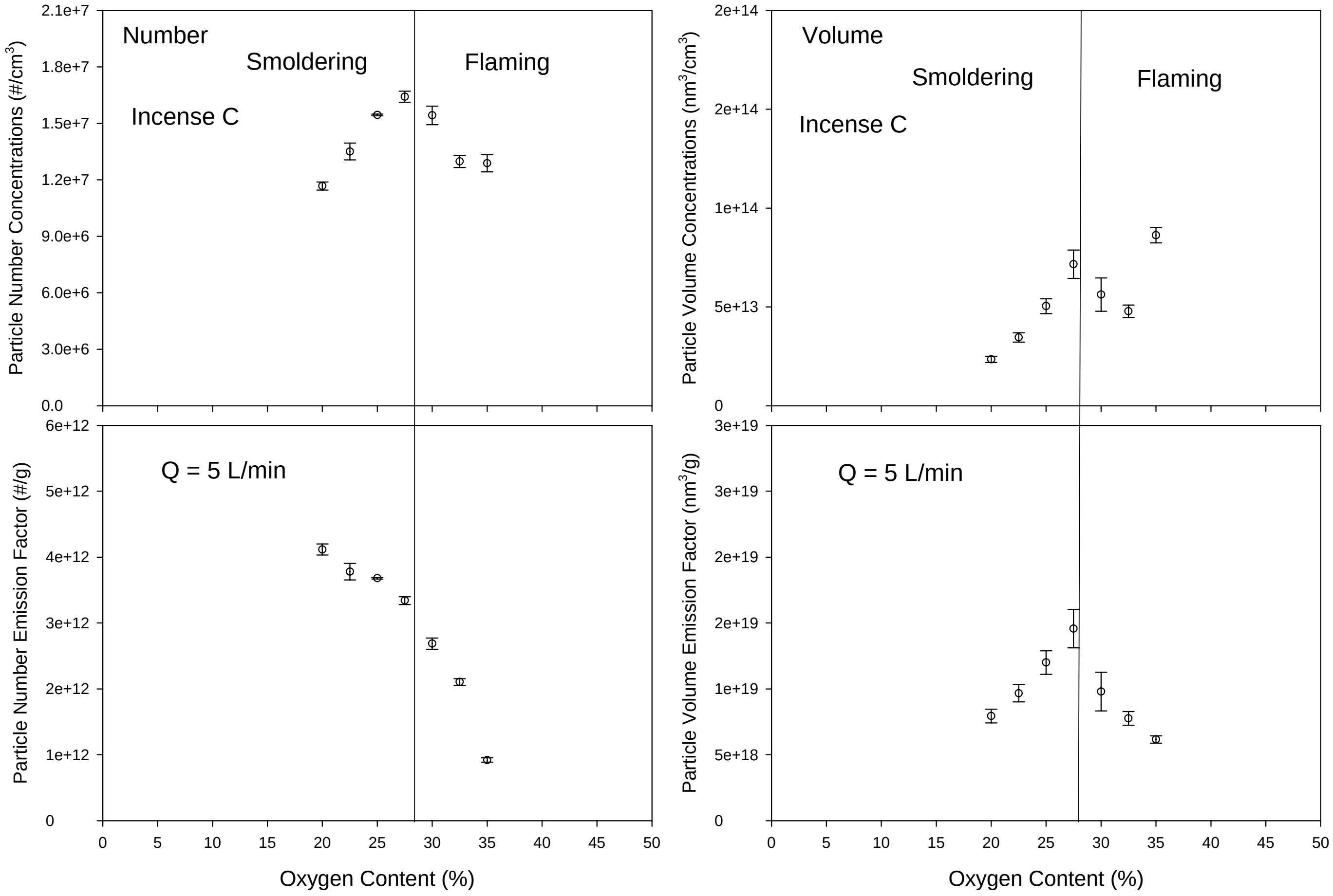


Figure 9. Submicron aerosol number and mass concentrations and their corresponding emission rates and factors versus oxygen contents at air flow rate of 5L/min for burning incenses C

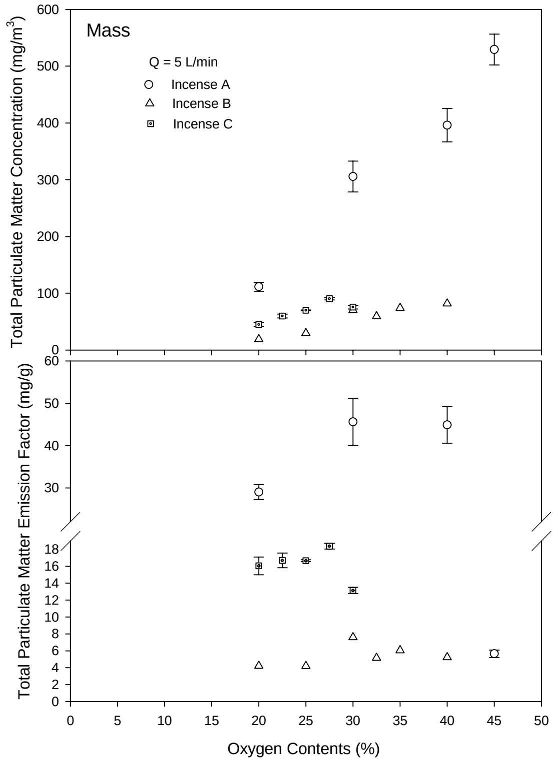


Figure10 Aerosol mass concentrations and emission factors from burning incense A、B and C under various combustion conditions

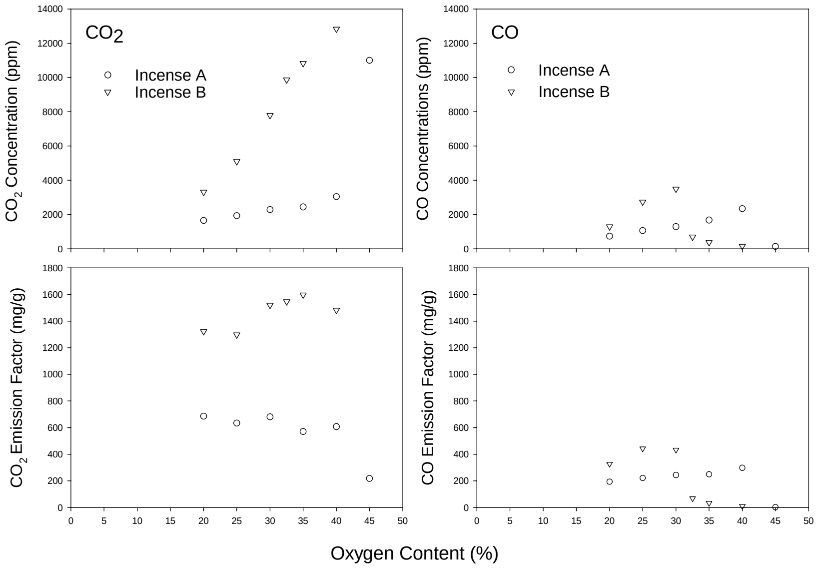


Figure 11 Comparison of CO_2 and CO emission concentrations, and corresponding emission factors from burning incenses A and B in various oxygen fractions

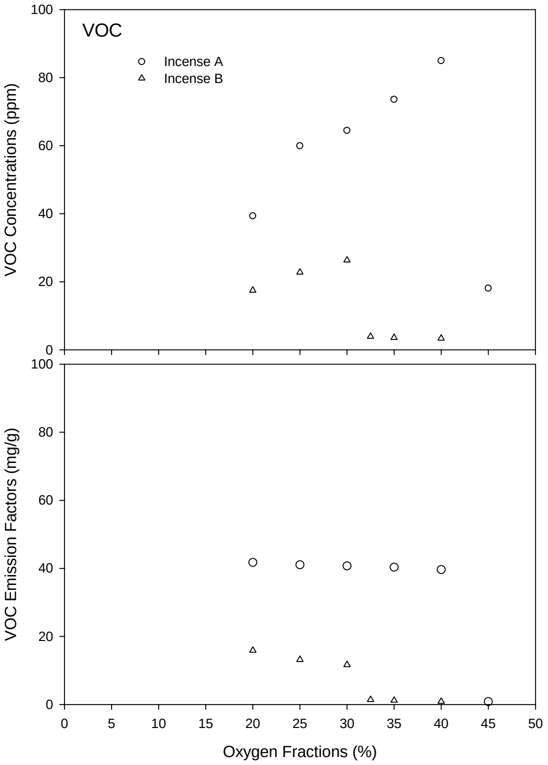


Figure 12 Comparison of VOCs emission concentrations, and corresponding emission factors from burning incenses A and B in various oxygen fractions

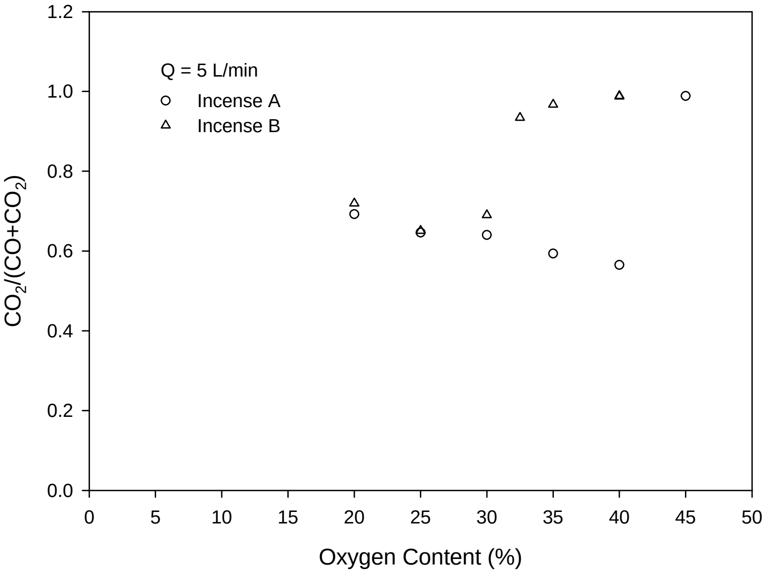


Figure 13 Comparison of combustion efficiency indices of incenses A and B in various oxygen fractions

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Effect of Air Flow on Emission of Smoldering Incense

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Burning incense sticks as a religious ritual is common in Chinese society. It is part of the daily routine of about 50% of families in Taiwan. Epidemiological studies indicated that exposure to incense smoke might be related to the occurrence of lung cancer (MacLennan et al, 1977), childhood leukemia (Lowergard et al, 1987) and brain tumor (Preston-Martin et al, 1982). Ames test identified the mutagenic effect of the incense smoke (Sato et al, 1980; Rasmussen et al, 1987; Chang et al, 1997).

The smoldering of incense is regarded as an incomplete combustion of biomasses, and takes a relatively long time. It results in the production of gaseous carbon monoxide, carbon dioxide, nitrogen oxides, polycyclic aromatic hydrocarbons (PAHs), formaldehyde, volatile organic compounds (VOCs) and chemical–bearing particles (Schoental et al., 1967; Lin and Wang, 1994; Lin and Tang, 1994; Lin and Lee, 1998). The diameter of the submicrometer particles produced by incense smoke was less than 1 μm. Therefore, the submicrometer particles produced by the smoldering of incense do not only have a higher chance of penetrating the alveolar region of human lungs. Yet, their number concentration and surface area were higher, enabling them better to carry pollutant matter. The constituents of the incense stick and the conditions of incense combustion (airflow, temperature, humidity and oxygen content) both affect in determining the characteristics of incense smoke. This work tried to simulate the combustion of incense at home or in the temple, to elucidate the characteristics of submicrometer particles and gas pollutant produced by incense smoke in controlled air flow in an attempt to correct the indoor contamination caused by incense burning.

MATERIALS AND METHODS

The joss sticks used in this study consisted of incense powder and a bamboo stick. The incense powder was a mixture of three varieties of dried vegetation, *Santalum album L.*, *Machilus nanmu Hemsl* and Pine oleoresin. The carbon, hydrogen and nitrogen contents in the joss stick were measured using an elemental analyzer (2400 CHN Elemental Analyzer, Perkin-Elmer, U.S.A.). The heat value was measured using an oxygen bomb calorimeter (1271 Oxygen Bomb Calorimeter, Parr Instrument Company, U.S.A.).

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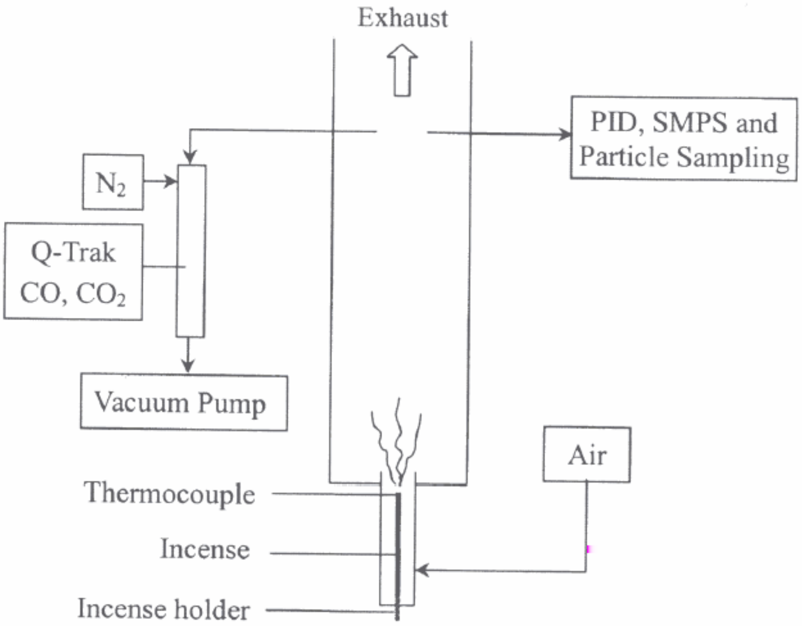

Figure 1. Incense combustion system.

A joss stick was ignited and inserted into an incense holder at the bottom of the smoldering chamber where the purified compressor air was supplied and regulated by mass flow controllers (Fig. 1). The surface temperature of the burning tip of an incense stick was monitored using a K-type thermocouple made of 79 μm nickel-aluminum and nickel-chrome wires. The incense smoke was led into a 7.3 L test chamber in which a probe (1/4-inch in diameter) for sampling particles was located 40 cm away from the bottom of the test chamber and 3.5 cm away from the wall. Before and after burning, an individual joss stick was weighed to determine the net loss of mass, enabling the incense-burning rate to be calculated.

Particles were counted and sized using a Scanning Mobility Particle Sizer (SMPS, Model 3934, TSI Inc., USA), which combined a differential mobility analyzer (DMA, Model 3071, TSI Inc.) with a condensation particle counter (CPC, Model 3022, TSI Inc.). The total particles were sampled with a quartz filter (37 mm, Pallgelman, U.S.A.) in a two-piece cassette at flow rate of 0.9~2 L/min for ten minutes to determine mass concentration of particles. A 1.4 L dilution chamber was annexed to the test chamber to determine the concentration of carbon monoxide, and carbon dioxide (Fig. 1). The incense smoke was diluted with pure nitrogen (99.99%, Shen Yi Gas Co., Taiwan) prior to it entered the dilution chamber. This step reduced the concentration of pollutants into the specified detectable ranges of 0-5000 ppm for CO_2 and 0-500 ppm for CO, of the real-time monitoring instruments. The Q-Trak™ Indoor Air Quality Monitor (Model 8550/8551, TSI Inc., U.S.A.) measured the CO_2 and CO concentrations with accuracy ±3 %. The MiniRAE 2000 Portable VOC Monitor (RAE SYSTEMS Inc., USA) with specified range of 0-10000 ppm and accuracy ±10 % measured the response of total VOCs with UV at 10 ev. Both zero calibration and span calibration were conducted for each instrument by following the manufacturers' instructions. For the responsive span calibration of the Q-Trak™, the reference CO (99.9%, Sanfu Gas Co., Taiwan) and CO_2 (99.99%, Sanfu Gas Co., Taiwan) were diluted, using high pure nitrogen (99.9995%, Sanfu Gas Co., Taiwan) to 395 ppm and 4050 ppm, respectively. And the standard isobutylene (100 ppm, RAE SYSTEMS Inc., USA) was used to calibrate the VOC Monitor.

The emission rates and emission factors of particles or gas were calculated using the conservation of mass, as follows.

$$V \times \frac{dCi}{dt} = R \times E_f - Q \times Ci \qquad (1)$$

where V (m^3) is the volume of the test chamber; C_i (mg/m^3 or particles/cm^3) is the concentration of gas or particles at a given time; R (g/hr) is the incense-burning rate; E_f (mg/g or particles/g) is the emission factor of each pollutant, and Q (5 L/min) is the air flow rate. In Eq. 1, dCi/dt=0 when each pollutant in the dilution chamber is in dynamic equilibrium, so the equation can be rewritten as follows;

$$E_f = \frac{Q \times C}{R} \qquad (2)$$

In Eq. 2, the emission rate was obtained by multiplying the flow rate by the concentration of pollutant and the emission factor, E_f, was the specific emission rate that was normalized to incense burning rate. The expression for the concentrations of gaseous pollutants was converted from ppm (v/v at 25℃, 1 atm.) to mg/m^3 based on the ideal gas law. In calculating the emission rate of total VOCs, the molecular weight of total VOCs was assumed to be 100 g.

RESULTS AND DISCUSSION

The incense used in this study consisted of carbon, hydrogen, nitrogen, ash and water, with weight percentages of 43.59, 5.4, 0.61, 7.72 and 7.39%, respectively. The heating value of the incense was 3934 Kcal/Kg. The incense underwent smoldering combustion. The maximum temperature of the burning tip, in which the pooled coefficient of variation (CV_{pooled}) was 0.04 (n_{total} =3x6), varied with the flow rate (Fig. 2). When the air flow rate was 1~5 L/min, the maximum temperature ranged from 328.2℃ (n=3, CV=0.03) to 452.9℃ (n=3, CV=0.02). When the air flow rate was 10~20 L/min, the maximum temperature reduced slowly from 253.0℃ (n=3, CV=0.04) to 160.3℃ (n=3, CV=0.06). The burning rate increased with the air flow rate up to 15 L/min at a temperature of 210.1℃ (n=3, CV=0.01), after which the burning rate decreased slowly. This result differed a little from that of the relationship between the burning rate and the inner temperature of foam obtained by Wang et al. (2003), who found that the burning rate was maximum at the maximum temperature. However, the results herein showed that the burning rate was maximum at a flow rate of 15 L/min, but not at maximum temperature, perhaps because the K-type thermocouple at high air flow rate, causing errors of measurement.

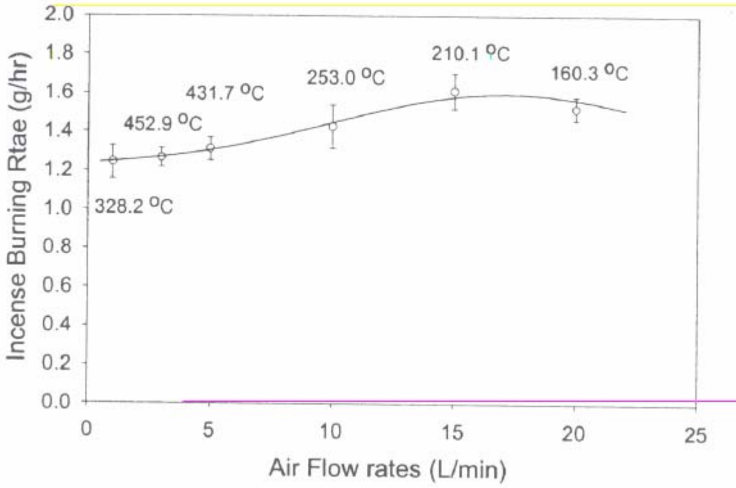

Figure 2. Burning rate and maximum temperature of burning tip at various air flow rates (Bar: mean ± standard deviation).

The count median diameter shifted from 242 to 120 nm as the air flow rate increased (Fig. 3). Additionally, the number concentration, the emission rate and emission factor for particle with size less than 250 nm showed that these parameters all increased with the air flow rate increasing, for the following two reasons. Firstly, the retention time and the coagulation of the highly number concentration of particle from the burning incense decreased slowly in the test chamber as the air flow rate increased. Secondly, the organic compounds on the surface of the particle were likely vaporized.

Figure 4 reveals that when the air flow rate was in the range 1~20 L/min, the total number concentration, emission rate and emission factor increased linearly with the air flow rate. The number emission rate and emission factor ranged from 7.25×10^{11} to 2.34×10^{13} #/hr and from 5.98×10^{11} to 1.53×10^{13} #/g, respectively. The mass concentration declined with the air flow rate increasing. However, the emission rate and emission factor after increasing, remains constant as the air flow rates increased. The mass emission rate with $CV_{pooled}=0.15$ (n=3x6) and emission factor with $CV_{pooled}=0.13$ (n=3x6) ranged from 10.6 mg/hr (n=3, CV=0.23) to 72.1 mg/hr (n=3, CV=0.19) and from 8.3 mg/g (n=3, CV=0.19) to 43.2 mg/g (n=3, CV=0.22), respectively. The volume concentration, emission rate and emission factor followed the same trend as the mass concentration against air flow rate. The volume emission rate and emission factors ranged from 2.06×10^{19} to 5.32×10^{19} nm^3/hr and from 1.7×10^{19} to 3.47×10^{19} nm^3/g, respectively. Lee et al. (2004) constructed a large environmental chamber to characterize the emissions of air pollutants from traditional incense. The emission rates for PM2.5 and PM10 were 28.4~372.6 and 31.9~389.4 mg/hr, respectively; the emission factor was 9.6~104 and 10.8~108.7 mg/g, respectively. Furthermore, Jetter et al. (2002) made a small chamber to improve the characterization of the emission of particulate matter from burning incense. The emission rates for PM2.5 and PM10 were 7.0~108 and 7.4~100

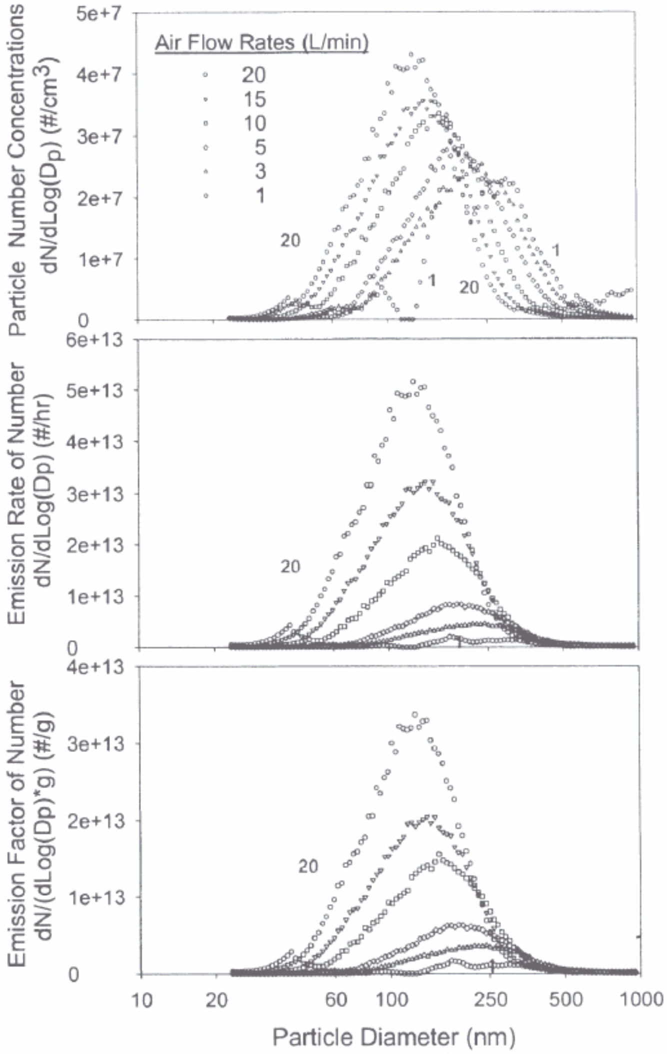

Figure 3. Aerosol number concentrations, emission rates and factors versus size of particles from burning incense at various air flow rates.

mg/hr; the emission factor was 5.0~55.7 and 5.4~59.4 mg/g, respectively. The emission rate and factor in this work differed a little from those of Lee and Jetter et al., perhaps because of differences of chemical composition, heating values of the incense and combustion conditions. Therefore, according to the aforementioned analysis, an air flow rate of 1 L/min air flow rate minimized PM emission, to the benefit of the health of people who burn incense.

The temperature of the burning tip varied with the air flow rate as follows; 328.2℃ (1 L/min), 452.9℃ (3 L/min), 431.7℃ (5 L/min), 253.0℃ (10 L/min), 210.1℃ (15 L/min) and 160.3℃ (20 L/min) (Fig. 2). The concentrations of CO_2, CO and TVOC, the emission rate and the emission factor increased with temperature from 328.2℃ to 452.9℃. The temperature and the concentrations of CO_2, CO and

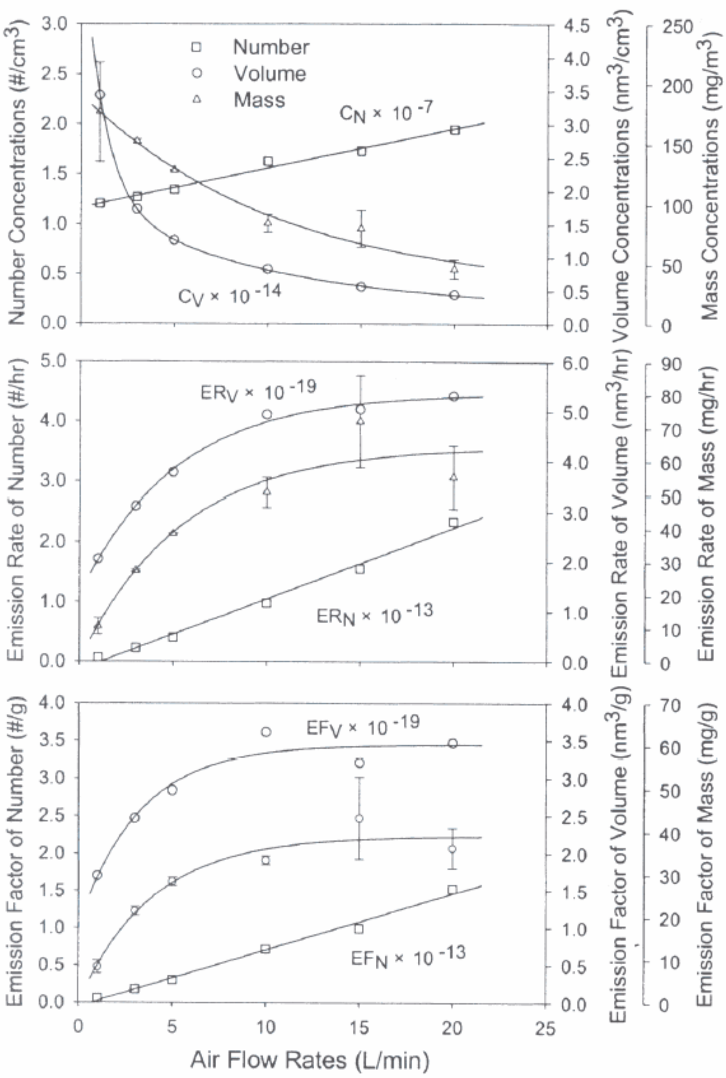

Figure 4. Aerosol number (volume and mass) emission concentrations, emission rates and factors from burning incense at various air flow rates (Bar: mean ± standard deviation).

TVOC declined when the air flow rate was higher than 15 L/min in Fig 5. However, the emission rates of CO_2, CO and TVOC steadily increased to stable levels, of between 1360 and 1379, 415, and between 77 and 78.9 mg/hr, respectively with the air flow rate increasing. The emission factors of CO_2, CO and TVOC also steadily increased to stable level between 866 and 900, between 264 and 271, and between 49 and 51.4 mg/g, respectively. The results showed that when the air flow rate was 1~20 L/min, the CO emission rate with CV_{pooled} =0.03 (n=2×6) and the CO emission factor with CV_{pooled} =0.03 (n=2×6) ranged from 48.7 mg/hr (n=2, CV=0.06) to 415.4 mg/hr (n=2, CV=0.03) and from 40.2 mg/g (n=2, CV=0.06) to 271.1 mg/g (n=2, CV=0.03); that of CO_2 with CV_{pooled} =0.05 (n=2x6) ranged from 210.3 mg/hr (n=2, CV=0.09) to 1379.8 mg/hr (n=2, CV=0.02) and from 173.5

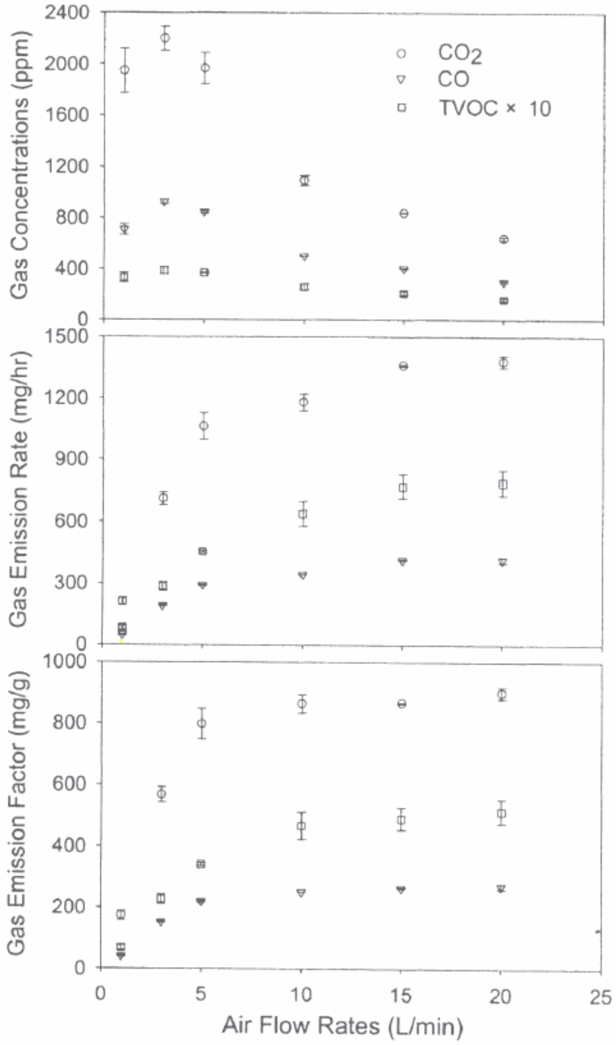

Figure 5. CO_2, CO, and TVOC emission concentrations, emission rates and factors from burning incense at various air flow rates (Bar: mean ± standard deviation).

mg/g (n=2, CV=0.09) to 900.3 mg/g (n=2, CV=0.03), and that of the TVOC with CV_{pooled} =0.08 (n=4×6) was ranged from 8.2 mg/hr (n=4, CV=0.12) to 78.9 mg/hr (n=4, CV=0.08) and from 6.8 mg/g (n=4, CV=0.12) to 51.5 mg/g (n=4, CV=0.08). Jetter et al. (1991) indicated that the emission rates of CO ranged from 159 to 227 mg/hr and Löfroth et al. (1991) found that the emission factors of CO ranged from 180 to 220 mg/g. Therefore, the range of emission rates obtained by Jetter et al. (1991) and the range of the emission factors obtained by Löfroth et al. (1991) include the range of emission rates and the emission factors of CO obtained herein. When the air flow rate was controlled at 1~20 L/min, the combustion efficiency with CV_{pooled} =0.01 (n=2x6) declined drastically from 0.73 (n =2, CV=0.008) to 0.67 (n =2, CV=0.004) as the air flow rate increased, indicating that combustion was not complete at a high flow rate, although the mass transfer of oxygen molecules to the incense burning tip had increased because increasing the air flow rate may also increase the heat loss rate. The combustion was incomplete at a high air flow rate, so the emission rate and emission factor of the gas pollutant were high increased with air flow rate increasing. In conclusion, an air flow rate of under 1 L/min minimized the emission rate and emission factors of gas pollutants from burning incense, and ensure more complete combustion, according to the characterization of gas emission.

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