

Rapid monitoring of volatile organic compounds: selected ion flow tube mass spectrometry (SIFT-MS)

G. Özcan Sinir, S. Suna*, C.E.Tamer

Department of Food Engineering, Faculty of Agriculture, Uludag University, 16059, Bursa, Turkey

Received July 17, 2014; Revised December 10, 2014

Selected ion flow tube mass spectrometry (SIFT-MS) is an analytical mass spectrometry technique that offers real time and rapid identification and quantification of gases in air and human breath, even it is trace amount. This technology is used rapid measurements of volatile organic compounds (VOC) and some inorganic gases.

SIFT-MS can be applied in food science, environment, medicine, and health and safety practice. In food science, several studies of volatile compounds in fruit and vegetables, nuts, cocoa and cocoa liquors have been reported. The applications of this technology is allowed to air analysis in following areas; hazardous toxic chemicals in shipping containers, diagnosis of non-invasive diseases through breath analysis and screening urine of workers for levels of toxic compounds.

Detection of ppt level of VOCs, real-time ambient air monitoring without any required sample preparation, and the direct analysis of moist samples are considered as the advantages of this technique. However, conflicts in compound identification and quantification between ionized fragments with the same molecular weight are the challenges of SIFT-MS.

The aim of this review is point out a new technology for measuring VOCs and outlines some results from several studies to show the application area of SIFT-MS in food science and other areas.

Keywords: Selected Ion Flow Tube Mass Spectrometry (SIFT-MS), volatile compound, fruits and vegetables, rapid monitoring.

INTRODUCTION

Selected ion flow tube mass spectrometry (SIFT-MS) was intended in the mid 1990's as an analytical method for the direct, accurate analysis of humid exhaled breath while avoiding redundant sample preparation into bottle or onto traps [1]. SIFT-MS is reversed the process which had been in use for the previous 30 years for determining rate coefficients. Main objective is if a rate coefficient and product ion(s) were known for an ion-molecule reaction, the concentration of neutral analyses can be found. The researchers assumed that this technology could be useful for breath research and the non-invasive diagnosis of illnesses [2]. Nowadays, SIFT-MS is used effectively an analytical mass spectrometry technique that provides rapid identification and quantification of trace amount of gases in air and human breath. This technology is offered for real-time analysis of trace concentrations of VOCs, which normally present in the vapour phase at room temperature, and some inorganic gases [3].

SIFT-MS has been applied in many areas, including food science, environment, medicine, and health and safety practice. The applications of this

technology is not limited with fruit and vegetable flavors, also this technique can be used in detecting levels of hazardous toxic chemicals in shipping containers, in rumen gas, research on diagnosis of volatile markers of infection and tumors in urinary headspace, and screening urine [4]. Ability to simultaneous measurement of the concentrations of many compounds in a single sample without chromatographic separation make SIFT-MS preferred for VOCs measurements [5].

OVERVIEW OF SIFT-MS

The operation of a SIFT-MS instrument is to determine the kinetic parameters of an ion-molecule reaction, which helps to determine a reaction rate coefficient and the product ion branching ratios. Francis [2] clearly explained the reactions during SIFT-MS operation. The basic principle of SIFT-MS is soft chemical ionization. An external ion source produces selected ions as H_3O^+ , NO^+ and O_2^+ , and forwards them to the ion injection orifice separately. Reagent ions do not react with air, N_2 , O_2 , Ar, CO_2 and water vapour [4], despite those ions react with most other gases and vapours [6]. These ions move through a flow

* To whom all correspondence should be sent.

E-mail: syonak@uludag.edu.tr

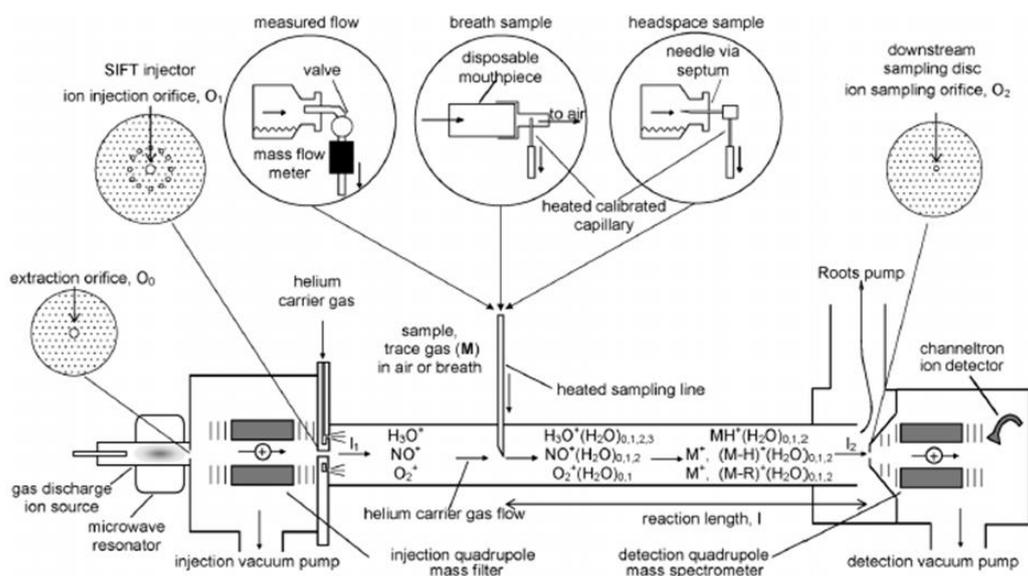


Fig. 1. Scheme of SIFT-MS [10].

tube carried by helium as a carrier gas [7]. Sampled air or reactant gas is injected into the flow tube via the inlet port and travels in the flow tube with the inert carrier gas at a known flow rate [8]. Trace gases in the sample react with precursor ion and generate product ions [7]. Product ions are detected by the quadrupole mass spectrometer and the target gas concentration can be calculated by using the reaction rate constant (k value) and product ion to precursor ion rate of the specific volatile compounds [8, 9]. The concentration $[M]$ of selected volatiles is calculated using the product count rate (I_p), reaction rate constant (k), precursor ions count rate (I) and reaction time (t) as follows: $[M]=I_p/Ikt$ [9].

Schematic of SIFT-MS is shown in Figure 1 [10].

OTHER ANALYTICAL TECHNIQUES FOR VOCS

There are different types of instruments exist for measuring VOCs in the air, headspace and breath. The traditional analytical methods to measure VOCs in the air and the headspace mostly require an isolation step before identifying the compounds. Some of the isolation methods used in previous studies is extraction, distillation, dynamic headspace, solid phase micro extraction (SPME), and liquid-phase micro extraction (LPME) [11-16]. To determine the VOCs in the breath requires real time measurements; therefore extraction step should be eliminated. In this respect, instrumentation that will be chosen need to be suitable for real time measurements.

Gas chromatography (GC) was used for separation and identification of compounds [14,16] equipped with Mass Spectrometry (MS), Flame Ionization Detector (FID) [12,17], Electron Capture Detector (ECD), Photoionization Detector (PID)

[18], Flame Photometric Detector (FPD) [5,20], Nitrogen Chemiluminescence Detector (NCD) and Sulfur Chemiluminescence Detector (SCD) [21,22].

Proton transfer reaction mass spectrometry (PTR-MS) is a newly developed technique, which allows rapid detection of aroma compounds in alcoholic beverages [23], breath analysis of banana aroma during eating [24], breath profile of smoker and non-smokers [25]. This technique was developed for on-line gas monitoring [26]. PTR-MS also used in chemical ionization (CI) techniques for detection of ionizing molecules with minimum fragmentation [27]. CI offers high sensitivity when the primary ions have enough time to react with the neutral compounds. PTR-MS instruments have recently incorporated linear and quadrupole ion traps and time-of-flight mass spectrometers (TOF-MS) for greater compound specificity. TOF-MS is well designed to give accurate mass data; however, a TOF tube does not give data associated with structural isomers [28,29].

Since there was interconnection between quantities of reacting species and reaction time, atmospheric pressure chemical ionization (APCI) systems have been developed [30]. Atmospheric pressure chemical ionization mass spectrometry (APCI-MS) is another technology which was developed to monitor aroma compounds in the breath during eating³¹. These two techniques use soft chemical ionization with the H_3O^+ as a reagent ion to monitor volatile organic compounds. APCI-MS was used for quantification of acetic acid, formic acid and furfural, which were biomass degradation products, within pretreated wheat straw hydrolyzates and bioethanol formation during fermentation³². While APCI-MS requires minimal sample preparation, results were found similar with high-performance liquid chromatography (HPLC) analysis.

All of these instruments have advantages and disadvantages. For example, instruments based on gas chromatography have the potential to analyze and quantify a large variety of molecules concurrently, with high sensitivity and specificity. However, some chromatographic techniques are allowed to sample loss during pre-concentration of the air.

Chemical ionization techniques can achieve high time resolution but some molecular species are difficult to identify and separate [33].

SIFT-MS APPLICATIONS IN FOOD SCIENCE

In food science, several fruit and vegetable studies of VOCs focuses on formation of Lipoxygenase (LOX) derived compounds. Monitoring the real time changes is essential to show quick formation of these compounds during ripening, storage or after tissue disruption. Studies showed that the concentration of (*Z*)-3-hexenal which is produced during the decomposition of 13-hydroperoxides of linolenic acid by LOX and hydroperoxide lyase in the LOX pathway [34] increased to a peak level in 3 min after tissue disruption by blending in tomatoes and tomatillos [35,36]. Also the concentration of (*E*)-2-hexenal, which is formed from the isomerization of (*Z*)-3-hexenal by cis/trans-isomerase in the LOX pathway [37,38], increased and reached peak level slightly later than (*Z*)-3-hexenal in tomatillos, tomatoes [39], jalapeno peppers [40], and strawberries [41].

The concentration change of volatile compounds during blanching, refrigerated storage, frozen storage and thawing was studied in jalapeno peppers [40], and strawberries [41]. The effect of ripening stage on volatile formation was studied in strawberries [41]. In early ripening stage, the concentration of LOX-derived volatiles was high and fruity esters were low, oppositely in last stage of ripening, reverse results were observed.

While this technology offers real time monitoring, some studies focused on volatile change in mouthspace during chewing and after swallowing. While concentrations of tomatoes and strawberries' volatile compounds increase in the mouthspace and nosespace during chewing, consumption of some foods, such as water, milk, and sodium caseinate solutions, can reduce volatile levels in the mouth, including malodorous garlic breath [42]. The Maillard reaction is also responsible for the formation of many volatiles. Real time formation of alkylpyrazines, aldehydes, acids, alcohols, esters, and ketones were easily measured during roasting with SIFT-MS [43]. Formation of many volatiles were peaked after 15 min. of cocoa roasting then decreased. Also volatile

formation increased with increasing temperature and peak time was shortened with decreasing pH during roasting. Both roasting and drying increase the formation of furan compounds in cocoa and carrots [43,44]. Langford et al.[45] compared the headspace VOCs concentrations of New Zealand cheeses marketed as parmesan, Italian Parmigiano Reggiano and Grana Padano cheeses in real time without any sample pre-concentration.

APPLICATIONS IN OTHER AREAS

SIFT-MS has been applied in many areas, including environment, medicine, and health. Some VOCs in exhaled breath are an indicator of non-invasive disease [5,8,46,47]. SIFT-MS techniques can be used in biological researches, which help to determine several metabolites in breath such as isoprene, ethanol, acetone and ammonia [48,49]. Monitoring these compounds by SIFT-MS, give an insight about the health condition of patient. Isoprene is a non-invasive marker of endogenous cholesterol in human breath and may help diagnosis of coronary artery disease as a result of increased cholesterol levels [50]. Also isoprene and ammonia are countable as markers of end-stage renal failure [51]. Measuring compounds concentration can be helpful to identify specific bacteria in the headspace of blood or urine sample [52], which can be helpful to identify antibiotics for target microorganism. Boshier et al. [53] used SIFT-MS to analyze trace gases within the breath of anaesthetized patients. This study showed the utility of on-line breath analysis during surgery for the monitoring of endogenous metabolites, anaesthetic gases and potential biomarkers of metabolic and oxidative stress during operation. Smith et al. [54] investigated the production of acetaldehyde from cancer cell lines (specifically the human non-small cell lung cancer cell lines SK-MES and Calu-1) *in vitro* and found that concentration of acetaldehyde in the headspace was proportional with the number of cancer cell lines in the environment. Another study focused on presence of formaldehyde in the headspace of the urine from the cancer patients. Spanel et al. [55] resulted that patients with bladder and prostate cancer had higher formaldehyde compared with urine from the healthy controls. Spanel and Smith [56] quantified trace levels of formaldehyde, acetaldehyde and propanol, potential cancer biomarkers, in breath by SIFT-MS. Smith et al. [57] determined ammonia, nitric oxide, acetone, ethanol and methanol which are the major volatiles in the urine. Abnormal levels of these compounds cause suspicions about alkaline urine, acidic urine or bacterial infection.

SIFT-MS is used for identifying dominant gases as hydrogen sulfide, methyl sulfide, and dimethyl

sulfide, in the rumen headspace [58]. Exhaust gas mixture was analyzed with SIFT-MS and found that aliphatic and aromatic hydrocarbons, aldehydes, ketones and alcohols were present with their fractions in both petrol and diesel engines [59].

CONCLUSION

Distinction of SIFT-MS from the other mass spectrometry analytical techniques is analyzing of VOCs in real-time without the requirement for calibration curves to calculate or determine analyze concentrations. It quantifies VOCs based on the ratio of product ion count to reagent ion count [5].

The advantages of SIFT-MS over other analytical techniques are detection of ppt level volatile by volume level, in real-time ambient air monitoring without any required sample preparation, and the direct analysis of moist samples. This technique allows to determine breath volatiles in real-time during eating and swallowing. Also determining of trace gases as a marker of cancer cells is beneficial to track metabolic activity both *in vitro* and *in vivo* [54], in addition to this, SIFT-MS technique may be used to predict early-stage tumors in the body as a non-invasive indicator in the near future [55].

However, the challenges of this technique are conflicts in compound identification and quantification between ionized fragments with the same molecular weight. SIFT-MS is in the early stage of development and further applications in the above-mentioned areas of researches and applications will be come out. With the continued progress to the SIFT-MS instrumentation and methodology, the new features of the technique become more widely applicable in other areas of researches.

REFERENCES

1. P. Spanel, D. Smith, *Curr. Anal. Chem.*, **9**, 523 (2013).
2. G.J. Francis, PhD Thesis, UC, Christchurch, New Zealand, (2007).
3. N. Sumonsiri, S.A. Barringer, *Curr. Anal. Chem.*, **9**, 631 (2013).
4. P. Spanel, D. Smith, *Eur. J. Mass Spectrom.*, **13**, 77 (2007).
5. D. Smith, P. Spanel, *Mass Spectrom. Rev.*, **24**, 661 (2005).
6. V.G. Anicich, JPL Publication, Pasadena, USA, (2003).
7. P. Spanel, K.D. Dryahina, D. Smith, *Int. J. Mass Spectrom.*, **267**, 117 (2007).
8. P. Spanel, D. Smith, *Med. Biol. Eng. Comput.*, **34**, 409 (1996).
9. P. Spanel, D. Smith, *Rapid Commun. Mass Spectrom.*, **13**, 585 (1999).

10. P. Spanel, D. Smith, *Mass Spectrom. Rev.*, **30**, 236 (2011).
11. N. Fischer, F. J. Hammerschmidt, *J. Chem. Microbiol. Technol. Lebensm.*, **14**, 141 (1992).
12. A.G. Perez, J.J. Rios, C. Sanz, J.M. Olias, *J. Agric Food Chem.*, **40**, 2232 (1992).
13. M. Larsen, L. Poll, *Z. Lebensm Forsch.*, **201**, 275 (1995).
14. R.U. Holt, *Acta Hort.*, **567**, 743 (2002).
15. V. Romeo, M. Ziino, D. Giuffrida, C. Conduurso, A. Verzera, *Food Chem.*, **101**, 1272 (2007).
16. Y. T. Zhang, G. X. Wang, J. Dong, C.F. Zhong, J. Kong, T. Z. Li, Z. H. Han, *Agric. Sci. China.*, **8**, 441 (2009).
17. R. Azodanlou, C. Darbellay, J.L. Luisier, J.C. Villettaz, R. Amado, *Eur Food Res Technol.*, **218**, 167 (2004).
18. R.M. Cavalcante, M.V.F. de Andrade, R.V. Marins, L.D.M. Oliveira, *Microchem. J.*, **96**, 337 (2010).
19. X. Fan, C.H. Sommers, D.W. Thoyer, S.J. Lehotay, *J. Agric. Food Chem.*, **50**, 4257 (2002).
20. X. Lu, C. Fan, J. Shang, J. Deng, H. Yin, *Microchem J.*, **104**, 26 (2012).
21. T.E. Siebert, M.R. Solomon, A.P. Pollnitz, D.W. Jeffery, *J. Agric. Food Chem.*, **58**, 9454 (2010).
22. J. Herszage, S. E. Ebeler, *Am. J. Enol. Vitic.*, **62**, 1 (2011).
23. E. Aprea, F. Biasioli, T.D. Mark, F. Gasperi, *Int. J. Mass Spectrom.* **262**, 114 (2007).
24. D. Mayr, T. Märk, W. Lindinger, H. Brevard, C. Yeretizian, *Int. J. Mass Spectrom.*, **223-224**, 743 (2003).
25. I. Kushch, K. Schwarz, L. Schwentner, B. Baumann, A. Dzien, A. Schmid, K. Unterkofler, G. Gastl, P. Spanel, D. Smith, A. Amann, *J. Breath Res.* **2**, 026002 (2008).
26. W. Lindinger, A. Hansel, A. Jordan, *Int. J. Mass Spectrom.*, **173**, 191 (1998).
27. M. S. B. Munson, F. H. Field, *J. Am. Chem. Soc.*, **88**, 2621 (1966).
28. C. J. Ennis, J. C. Reynolds, B. J. Keely, L. J. Carpenter, *Int. J. Mass Spectrom.*, **247**, 72 (2005).
29. M. M. L. Steeghs, C. Sikkens, E. Crespo, S. M. Cristescu, F. J. M. Harren, *Int. J. Mass Spectrom.*, **262**, 16 (2007).
30. F. W. Karasek, O. Hutzinger, S. Safe, *Plenum Press*, New York, (1985).
31. B.A. Harvey, J. Barra, *J. Eur J Pharm Biopharm.*, **55**, 261 (2003).
32. S. M. Davies, R. S. Linforth, S. J. Wilkinson, K. A. Smart, D. J. Cook, *Biotechnol. Biofuels*, **4**, 28 (2011).
33. L. Kaser, T. Karl, R. Schnitzhofer, M. Graus, I. S. Herdinger-Blatt, J. P. DiGangi, B. Sive, A. Turnipseed, R. S. Hornbrook, W. Zheng, F. M. Flocke, A. Guenther, F. N. Keutsch, E. Apel, A. Hansel, *Atmos. Chem. Phys.*, **13**, 2893, (2013).
34. P.A. Luning, A.T. Carey, J.P. Roozen, H.J. Wichers, *J. Agric. Food Chem.*, **43**, 1493 (1995).
35. Y. Xu, S.A. Barringer, *J. Agric Food Chem.*, **57**, 9108 (2009).
36. Y. Xu, S.A. Barringer, *J. Food Sci.*, **75**, 352 (2010).
37. E.J. Stone, R.M. Hall, S.J. Kazeniac, *J. Food Sci.*, **40**, 1138 (1975).

38. M. Petro-Turza, *Food Rev. Int.*, **2**, 309 (1986).
39. Y. Xu, S.A. Barringer, *J. Food. Sci.*, **75**, 268 (2010).
40. C. Azcarate, S.A. Barringer, *J. Food. Sci.*, **75**, 710 (2010).
41. G. Ozcan, S.A. Barringer, *J. Food. Sci.*, **76**, 324 (2011).
42. A. Hansanugrum, S.A. Barringer, *J. Food. Sci.*, **75**, 549 (2010).
43. Y. Huang, S.A. Barringer, *J. Food Sci.*, **76**, 279 (2011).
44. H. Duan, S.A. Barringer, *J. Food Proc. Present.*, **36**, 46 (2012).
45. V.S. Langford, C.J. Reed, D.B. Milligan, M.J. McEwan, S.A. Barringer, W.J. Harper, *J. Food Sci.*, **77**, 719 (2012).
46. P. Spanel, S. Davies, D. Smith, *Rapid Commun. Mass Spectrom.*, **12**, 763 (1998).
47. P. Spanel, S. Davies, D. Smith, *Rapid Commun. Mass Spectrom.*, **13**, 1733 (1999).
48. A.M. Diskin, P. Spanel, D. Smith, *Physiol. Measur.*, **24**, 191 (2003).
49. W. Cao, Y. Duan, *Clin Chem.*, **52**, 800 (2006).
50. N. Marczin, M.H. Yacoub, IOS Press, Amsterdam, Netherlands, (2002).
51. S. Davies, P. Spanel, D. Smith, *Nephrol. Dial Transpl.*, **16**, 836 (2001).
52. P. Spanel, A.M. Diskin, S.M. Abbott, T. Wang, D. Smith, *Rapid Commun. Mass Spectrom.*, **16**, 2148 (2002).
53. P.R. Boshier, J.R. Cushnir, V. Mistry, A. Knaggs, P. Spanel, D. Smith, G.B. Hanna, *Analyst*, **136**, 3233 (2011).
54. D. Smith, T.S. Wang, J. Sule-Suso, P. Spanel, A. El Haj, *Rapid Commun. Mass Spectr.*, **17**, 845 (2003).
55. P. Spanel, D. Smith, T. A. Holland, W. Al Singary, J. B. Elder, *Rapid Commun. Mass Spectrom.*, **13**, 1354 (1999).
56. P. Spanel, D. Smith, *J. Breath Res.*, **2**, 046003 (2008).
57. D. Smith, P. Spanel, T.A. Holland, W. Al Singari, J.B. Elder, *Rapid Commun. Mass Spectrom.*, **13**, 724 (1999).
58. R.J. Dewhurst, R.T. Evans, T.T. Mottram, P. Spanel, D. Smith, *J. Dairy Sci.* **84**, 1438 (2001).
59. D. Smith, P. Cheng, P. Spanel, *Rapid Commun. Mass Spectrom.*, **16**, 1124 (2002).

БЪРЗ МОНИТОРИНГ НА ЛЕТЛИВИ ОРГАНИЧНИ КОМПОНЕНТИ: SIFT-МАССПЕКТРОМЕТРИЯ

Г. Йозджан Синир, С. Суна*, Дж.Е. Тамер

Университет на Улудаг, Факултет по селско стопанство, Бурса, Турция.

Постъпила на 17 юли, 2014 г.; приета на 10 декември, 2014 г.

(Резюме)

SIFT-мас-спектрометрията (SIFT-MS) е аналитична мас-спектроскопска техника, която предлага бърза идентификация и количествено определяне в реално време на газове във въздуха и човешки дъх, дори и в случаите на незначително количество на газа. Тази технология се използва за бързо измерване на летливи органични компоненти и някои неорганични газове. SIFT-MS може да се прилага в науката за храненето, околната среда, медицината, здравеопазването и техниката за безопасност. В науката за храненето са представени редица изследвания на летливи компоненти в плодове и зеленчуци, ядки, какао и какаови ликьори. Приложенията на тази технология позволява анализ на въздуха в следните области: опасни токсични химикали в контейнери за транспортиране, неинвазивна диагностика на заболяванията чрез дъха, анализ и скрининг на урина за нива на токсични съединения на работниците. За предимствата на тази техника се считат откриване на пррт нива на летливи органични компоненти, наблюдение в реално време на атмосферния въздух без никаква подготовка на пробите и на пряк анализ на влажни проби. Въпреки това, предизвикателства на приложение на метода са трудности в идентификацията и количественото характеризиране на химични съединения и йонизирани фрагменти със същата молекулна маса.

Целта на настоящия обзор е представянето на една нова технология за измерване на летливи органични съединения и запознаване с резултатите от някои изследвания, които дават информация за областта на приложения на SIFT-MS в науката за храната и в други области за анализ на следи от газ във въздуха, издишвания от човека въздух и парите в горната част на колони с течности.