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Planar Drift Tube for Ion Mobility Spectrometry

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Abstract: The drift tube in ion mobility spectrometry is the component of central importance, where sample vapors are ionized and where ions are separated on the basis of gaseous mobility in a comparatively weak electric field. Construction of drift tubes is labor intensive and costly when built with precision machined components and an alternative design, fabricated using photolithography methods with planar drift plates, is described. Diagnostics of performance including response toward electric fields, peak shape of mobility spectra, determined values for reduced mobility coefficients, and patterns of response to changing vapor concentrations were consistent with conventional drift tubes. Neither ion losses nor band broadening were unexpectedly large though ultimate measures of performance were limited by the unavailability of drift tube components with rectangular profiles and by an imperfect reaction region design. The cost of making drift tubes is calculated as roughly 10% of that for conventional designs.

Keywords: Ion mobility spectrometry, Drift tube, Photolithography, Circuit board

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INTRODUCTION

Ion mobility spectrometry (IMS) is found today for critical measurements in venues for military preparedness and for commercial aviation security.^[1] Analyzers based on IMS are used to screen carry-on baggage for explosives in airports worldwide and to monitor materiel and personnel for chemical warfare agents in battlefields.^[2] The importance of such measurements for the well-being of soldiers, or the traveling public, and the numbers of IMS analyzers distributed (>50,000) are unique for sophisticated analyzers of any kind. Other and minor applications of IMS include monitoring gases emitted from stacks at industrial sites,^[3,4] detecting impurities in semi-conductor manufacturing,^[5,6] and screening air quality for volatile organic contaminants on the International Space Station.^[7,8] Mobility spectrometers are attractive through analytical performance with low limits of detection, easily interpreted spectral profiles, and high speed of response. Additional benefit may be found in the economies of size, weight, and power. Since measurements can be made at ambient pressure, IMS instruments may be uncomplicated and portable with complete analyzers now available as palm-sized or hand-held devices.^[9]

The central component in an IMS analyzer is the drift tube where gas phase ions, derived from sample, are characterized for mobility in a weak electric field. In a conventional analyzer, this is comprised of over two dozen components with circular cross section, including an ion source, an ion shutter, multiple drift and insulating rings, an aperture grid, and a detector, commonly a Faraday plate.^[1,10] Components are arranged so that sample vapors are introduced into a reaction region, containing an ion source such as ^{63}Ni , in a supporting atmosphere of purified air or nitrogen. In the reaction region, sample vapors and reactant ions collide and form product ions that reflect the chemical composition of the sample. Ions from the reaction region are injected as an ion swarm into a linear voltage gradient and develop a drift velocity governed by the electric field strength and the mobility coefficient for the ion swarm. Drift velocity is determined using the time of passage of the swarm through a fixed distance between the ion shutter and detector, i.e., the drift region. Despite certain common features of components, drift tubes from manufacturers and researchers have a broad range of designs and operating parameters with little movement toward a common instrument standard.^[11–14] Nonetheless, all these instruments share a single design constraint: the drift tubes are comparatively complex and expensive. These costs arise principally from the precision manufacture of components and the labor-intensive assembly of pieces. Such disadvantages have been characteristic of IMS drift tubes from their inception.

Analytical grade drift tubes were first described and commercialized in 1970^[15,16] and were assembled using metal rings in a stack under gentle compression and separated from one other by small sapphire balls. The drift rings were placed at specific potentials defined by a voltage divider and an electric field (200–300 V/cm) was established along the central axis of the drift ring

assembly. This drift tube was derived from an earlier vacuum based unit and the first units were also housed inside a stainless steel vacuum chamber though operated at ambient pressure. Mobility spectra for a large number of chemicals were obtained with this drift tube design^[17–19] between 1970 and 1980 though the analytical utility was hindered by diffusion of sample neutrals into the drift region. This complicated the reproducibility and interpretation of mobility spectra.^[20,21] and was later improved when the sapphire balls were replaced by Teflon[®] or Macor[®] insulating rings, providing isolation of the supporting atmosphere inside the drift tube. A transformation in drift tubes occurred with a fast responding, low memory effect design^[22] made possible by passing drift gas from the detector, through the drift region and then through the reaction regions to vent. Sample was introduced into the reaction region and swept from the drift tube establishing a residence time for sample neutrals in the reaction region (fixed by the volume of the reaction region and gas flow rate) and preventing ion-neutral clustering in the drift region of the analyzer. The stacked ring design with minor variations can be found in the most popular IMS analyzers including the handheld CAM (chemical agent monitor) and the model 400 Ionscan explosive detectors (by Graseby Dynamics and Barringer Research Ltd., respectively, both now Smiths Detection) and the Itemizer (Ion Track, Inc., now GE Security). So long as high purity of the supporting atmosphere inside the drift region is preserved, the current practice of the technology can tolerate differing size or shapes of drift rings and operating conditions of electric field strength or shutter voltages.^[23]

Simplified design or construction can be seen in research grade analyzers where metal drift rings were applied to the outside of a tube of a non-conducting material, either glass^[24] or Teflon[®].^[25] The drift rings may be substituted as thin metal bands onto a tube or as conventional drift rings fitted over a tube. In either design, a tube was substituted for insulating rings minimizing contamination by diffusion from outside the analyzer and reducing the number of components. An electrical harness was to establish potentials on individual drift rings. A further simplification was made with drift rings attached directly to a circuit board holding the voltage divider, the shutter controller and the detector amplifier. This design was incorporated in the design of a palm sized analyzer, the Lightweight Chemical Detector.^[26]

An alternative to discrete drift rings was a single ceramic or glass tube coated with a thin film of semi-conducting ink on the inside wall.^[27–30] An electric field was created with the semi-conducting ink, when attached to high voltage and ground at each end of the drift tube eliminating individual rings, voltage divider and most of the electrical hardness.^[27,28] Performance was comparable to a drift tube with discrete drift rings and insulators and the advantage of this simplicity of this design was complicated by reproducibly forming an even thin film of ink inside a tube.

A few unconventional designs for IMS analyzers have been demonstrated as shown with conducting rods between two planes defining a rectangular body.^[31] In this design, ions were moved in an oscillating electric field to

provide a type of notch filter for ions. Although this analyzer was not operated as a regular mobility spectrometer, results suggested that massive reduction in signal through ion losses by collision on walls did not occur making possible fabrication with inexpensive photolithography methods as found in printed circuit board technology.

The present work was motivated by the barrier of high cost of labor for precision machining and assembling of conventional drift tubes. A planar geometry was used where electric fields are established using drift plates, versus rings, on each of two the planes defining a drift region. The analyzer planes are separated by insulating rails and held in a retaining frame. In other aspects, the drift region has conventional components of ion shutter, aperture grid, and voltage divider. As this drift tube is found to be a substitute for other geometries, flexibility of designs and configurations of mobility spectrometers may be improved while costs are reduced. The objective of this work was to demonstrate the concept of a mobility spectrometer using planes fabricated with circuit board technology and to document analytical performance. Circuit boards were seen as rapid and inexpensive for prototyping and testing a design concept which could later be replaced with more durable and suitable ceramic or glass substrates.^[32] Although the rectangular geometry might disfavor the word tube (as in drift tube against the accurate, drift block or drift chamber), drift tube will be used anachronistically throughout this work.

EXPERIMENTAL

Instrumentation

The drift tube was assembled from two printed wiring (circuit) boards with dimensions of 63.5 mm × 96.5 mm and each with nine evenly spaced drift plates (63.5 mm × 5 mm) as shown in Figure 1. The drift plates, holes and wiring patterns were fabricated using a template and photolithographic techniques (PCBexpress, Mulino, OR, USA). Two circuit boards were separated by Teflon[®] gaskets to define the volume (1.3 cm × 2.5 cm × 7.4 cm, or 24.05 cm³) of a drift tube and were retained by metal panels with metal screws and bolts (Figure 2). The drift tube was completed with electrical connections and a voltage divider (Figure 2). The voltage divider was made using 2 M Ω resistors and was used to provide specific potentials to each drift plate forming an electric field in the drift tube. The high voltage supply was designed and built at NMSU.^[33] Other components of the drift tube included an ion shutter, aperture grid and detector. These were built as discrete components with rectangular cross sections and were fitted between the planes using predrilled holes. The ion source was electron emission from 370 MBq (10 mCi) of ⁶³Ni coated on a thin (0.1 mm) wall tube ~5 mm long × 6 mm ID. This source was placed in a 1/8" Swagelok union and attached to an end wall or plug of the drift tube; all gas flow was

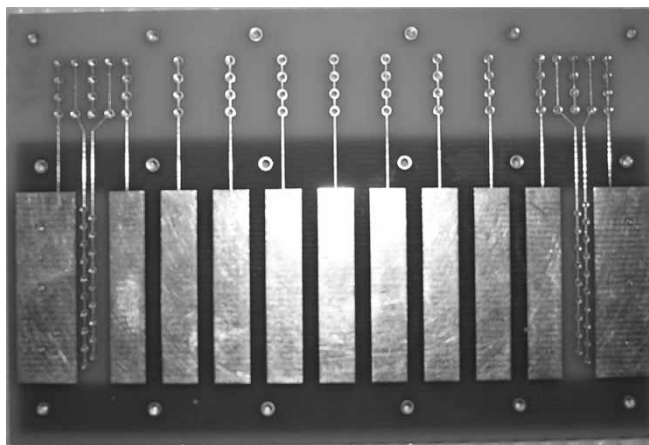


Figure 1. Photograph of inside of one side of a planar drift region for an ion mobility spectrometer. The electric field needed for ion motion is established on drift plates on the wire board using the drift plates and a voltage divider assembled on the board.

exhausted through this fitting. An ion shutter, with rectangular shape to fit inside the cross section of the drift tube, consisted of a metal frame with a $10\text{ mm} \times 30\text{ mm}$ window. Stainless steel wires were soldered in parallel over the window and two frames were placed together with a separation of $\sim 1.25\text{ mm}$; windows were positioned with an inter-digitated arrangement of

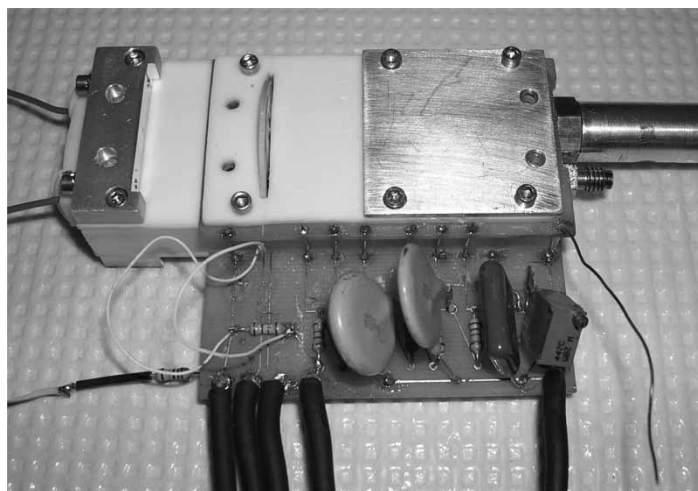


Figure 2. Photograph of planar mobility spectrometer fitted with voltage divider and ion source (at left).

wires and line-of-sight distances between wires of ~ 0.25 mm, center-to-center. Potentials on the wires of the ion shutter were controlled by electronics made at NMSU.^[10] An aperture grid was placed in front of the detector and was made from a single window of circuit board, as described above for the ion shutter. Distance between the aperture grid and detector was 1 mm and the detector was a stainless steel plate (20 mm \times 10 mm). The detector was connected via coaxial cable to the amplifier.

The drift gas was house air prepared with a Whatman Pure Air Generator (Rockville, MD, USA) and purified using several large scrubbing towers (1 m long, 30 cm ID) containing 5 Å molecular sieve. Moisture in the scrubbed air was ~ 5 ppm and was measured using a model MIS-2 moisture meter (Pana-metrics, Boston, MA, USA). Flow of the drift gas was introduced into the drift tube at the detector and passed using through the drift tube to vent. Gas flow was controlled at 100 to 300 mL/min using a model GR 116-3-A-PO mass flow controller (Fathom Technologies, Round Rock, TX, USA). Temperature of the spectrometer was ambient at $\sim 25^\circ\text{C}$. The pulse time for the ion shutter was 300 μs and each scan was initiated on the rising edge of the rectangular shutter pulse, the time scale zero was set at the center of the rectangular waveform. The sample inlet was an exponential dilution flask consisting of a heated three neck 500 mL glass round bottom flask. The flask included a port for gas in (via mass flow control), gas out (through a short length of 1/16" Teflon tubing), and a port to inject sample vapor.

Mobility spectra were acquired using a model 6024E signal acquisition board (National Instruments, Austin, TX, USA) and Labview software (LinearIMS.1.0).^[33] Every mobility spectrum consisted of 1000 individual data points taken at a frequency of 33 kHz; 50 to 200 spectra were accumulated and averaged to improve signal to noise ratio. Mobility spectra (ASCII, 0.5 to 1 MB) were obtained as a function of the dilution time using vapors delivered from an exponential dilution flask.

Chemicals and Reagents

All chemicals used in characterizing the drift tube were ketones with purity of 98% or better and were purchased from Chem Services (West Chester, PA, USA) or Aldrich (Milwaukee, WI, USA). All were used as obtained without further purification.

Procedures

Spectra of Reactant Ions

Spectra of the reactant ions were obtained throughout a range of voltages applied to the planar mobility spectrometer spanning an electric field inside

the drift tube from 100 to 350 V/cm, normal operating ranges for mobility spectrometers. No additional control was made to electric fields in the aperture-to-detector region.

Spectra for Ketones

After the injection of a pre-calculated amount of neat ketone into the exponential dilution flask using a GC syringe (Hamilton Co., Reno, NV, USA), the initial concentration was decreased by dilution in a flow of purified air (150 mL/min). Alternatively, for qualitative studies, samples were introduced into the mobility spectrometer by allowing head space vapors to diffuse into the ion source from a liquid reservoir. A drift gas flow of 800 mL/min of air through the drift tube of the mobility spectrometer helped to establish constantly clean and reproducible conditions inside the instrument and this high flow was needed to bath the ion source in a purified atmosphere. Otherwise, the spectrometer could be operated with gas flows of 100 to 300 mL/min. A homologous series of seven ketones (2-propanone to 2-nonanone) in air was introduced successively into the planar mobility spectrometer at initial concentrations from ~ 0.1 to 20 $\mu\text{g/L}$ and mobility spectra were recorded continuously throughout the dilution experiment. After about six to eight minutes, concentrations for analyte were below the detection limit of the mobility spectrometer and the experiment was stopped.

RESULTS AND DISCUSSION

Potential Contours Inside the Drift Tube

The peak shape or bandwidth in a mobility spectrometer is established largely by the pulse width or time for injection of the ion swarm into the drift region and the diffusion of ions while the swarm is moving toward the detector.^[34] Further broadening can occur when the ion densities exceed $\sim 10^8$ ion/cm³ or when ion molecule reactions occur during ion drift. Our pulse widths provided ion densities ten fold below that of this limit and ketones yield long-lived ions ($t_{1/2} > 20$ ms) in a rigorously purified supporting atmosphere; therefore, band broadening here was controlled by or attributed exclusively to pulse width and ordinary diffusion of the ion packet. This conclusion is dependent upon assurances that the electric fields are not distorted. Imperfections or distortions in the electric fields established by the drift rings and voltage divider can produce second order broadening of peaks or can adversely affect ion transmission efficiency. These imperfections can be seen in diagrams of potential contours inside the drift tube and are created using commercially available software provided with dimensions and shapes of the drift tube.^[10,25] As irregularities in these field contours arise, ion losses and band broadening will occur and the new planar geometry

was initially considered prone to distortions of contours lacking some of the symmetrical of cylindrical drift tubes. Modeling of field lines with SIMION was made to examine optimum design dimensions and analyze the configuration used in this work.

Results from modeling contours in a planar analyzer are shown in part for nine drift plates each 5 mm long with a gap of 2.5 mm between plates as shown in Figure 3. The figure shows the side view of a cross section of the drift tube, an aperture grid with detector on the right and the ion source and shutter grid on the left. A uniform electric field exists when the equipotential contours are parallel and evenly spaced within the drift region and this is observed in the center axis of the analyzer, extending toward the walls. However, distortion of electric fields near the walls of the analyzer is also evident with curvature of the contours. This is seen in Figure 3 at distances from 0 to 0.05 cm from the surface of the planes as weakened electric field with increased distances between neighboring equipotential lines. Thus, ions passing through the volume of non-homogenous potential contours will be decelerated compared to those in the region of the drift tube with parallel potential contours and band broadening will occur. The volume where field distortions exist was $0.925 \text{ cm}^3 \times 2 = 1.85 \text{ cm}^3$ and constituted 7.69% of the total volume in the drift region; consequently, band broadening from this effect can be expected to be minor. Indeed, the effect may be even smaller than this since charge accumulates in air at ambient pressure on non-conducting surfaces of the circuit board. The aggregation of charge will modify, or perhaps correct, distortions in potential gradients^[10] and such affects are not modeled in the SIMION software. Consequently, the picture provided in Figure 3 may be substantially less distorted in practice from charge accumulation. Indirect support for this exists in comparisons of peak shape in the theoretically perfect drift tube (a continuous semi-conducting surface) and a traditional segmented design where differences in band broadening were not measurable.^[28]

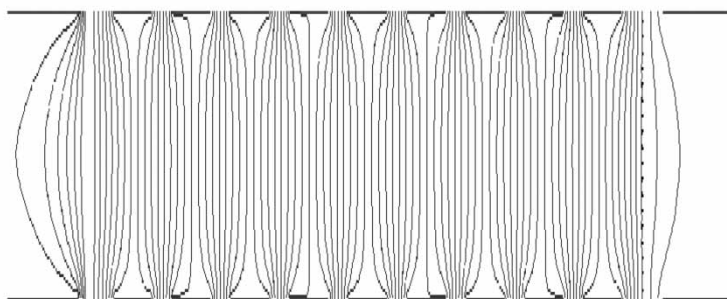


Figure 3. Electric field lines in a planar drift region with nine drift plates 5 mm electrodes – 2.5 mm gap.

Other dimensions of the drift region were modeled with SIMION to explore the effects of width of the drift plates and the gap between the plates on homogeneity of the potential contours. Certain trends were observed: A). increases in the plate width with decreases in the gap between plates cause increased distortion of the electric fields, B) large distances between the plates or a lower total number of electrodes and a smaller electrode diameter improved the homogeneity in electric fields. Emphasis is not given to these studies owing to the limitation of space charge effects. Still, a wide range of designs was seen as realistic and the design shown in Figure 3, though not optimum, was employed through the experiments described below.

Peak Shape and Intensity for Reactant Ions

The quality of performance of mobility spectrometers can be quantified as the position of the peak on the x-axis divided by the width of the peak, as in other ion separation methods such as mass spectrometry.^[35] This dimensionless ratio, termed resolution, is a preliminary measure of performance and most drift tubes in IMS exhibit values of ~ 30 . Results from the planar mobility spectrometer in a first configuration are shown in Figure 4 for the reactant ions in positive polarity (calculated as 90% $\text{H}^+(\text{H}_2\text{O})_3$ at moistures and temperatures of the supporting atmosphere from the drift gas). Values are plotted against the electric field, from 100 to 350 V/cm, applied to the analyzer. At low field strengths, the drift time is large and band broadening is large perhaps from prolonged residence time of ions in the drift region. As the electric field is increased, the drift time is decreased and peak width also is decreased. Finally, the time of drift is so short that the shutter pulse width limits performance.

The pulse width for the ion shutter was 300 μs and was only one limitation of the ion shutter used in the early studies seen in Figure 4. Since the cross section of the drift tube was rectangular, existing shutters with cylindrical drift tubes were not suitable for direct application and a rectangular shutter was crafted. This unrefined approximation of a Bradbury Nielsen shutter functioned but did operate at shutter pulse widths below 300 μs without unacceptable loss in signal to noise ratio. In contrast, other ion shutters, based on the Chemical Agent Monitor, can produce signal at pulse widths as low as 50 μs . Thus, comparison in absolute performance of other conventional drift tubes,^[36,37] is prevented by the behavior of the ion shutter and these studies can serve only for optimization or internal comparison of response. Despite the poor performance of the ion shutter, results suggest that the planar design provided mobility spectra in general manner as expected in conventional drift tubes. As the electric field is doubled from 100 to 200 V/cm, the resolution improved from ~ 8.5 to 13, and reached a maximum near 13 at ~ 200 V/cm. This

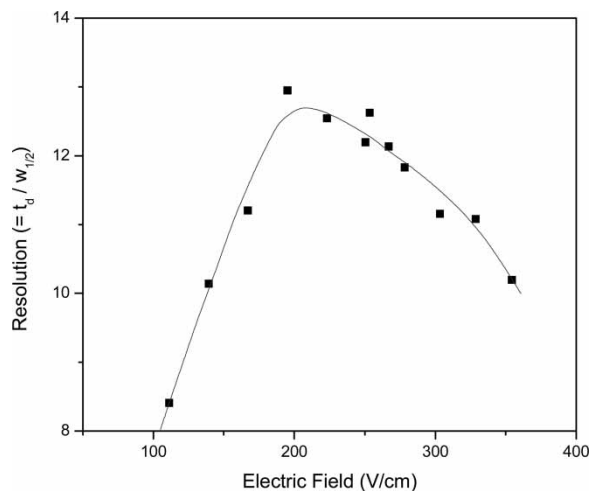


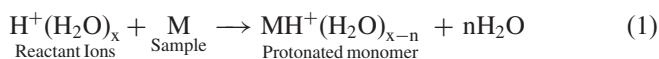
Figure 4. Values for $t_d/w_{1/2}$ from extremes of electric field strength in the drift region. Aperture to detector potentials were not controlled independently and will contribute to overall performance.

decreased slowly to ~ 10 as the field was further increased to 350 V/cm. Much of this variation can be attributed to changes in the aperture to detector region which is varied with the entire voltage divider and was not independently controlled in this unit.^[23]

One other cause of band broadening is purity of the supporting atmosphere including moisture inside the drift region where reactions between impurities and ions passing between the ion shutter and detector can lead to peak broadening or distortion.^[34] Although the drift gas was purified and would not directly contribute to contamination of the supporting atmosphere, contamination from the wiring board material was readily observed as distortions in mobility spectra as the board is heated. Though the boards were used at ambient temperature, the level of vapor emission from the board was not known directly. However, levels of impurities will be observed as changes in the reduced mobility of the reactant ions. The calculated value here was $2.14 \text{ cm}^2/\text{Vs}$ and is comparable to $2.09 \text{ cm}^2/\text{Vs}$ for a clean hydrated proton at 25°C and similar level of moisture. Consequently, there is no basis for substantial contamination of the supporting atmosphere by vapor emissions of the circuit board. Nonetheless, circuit boards are understood as convenient only for quick studies such as this and are wholly unsuitable for refined instrumentation where a material with high temperature stability and low vapor emissions is needed. Drift times for the reactant ion peak ranged from 9.22 ± 0.03 to 9.28 ± 0.03 ms over all measurements and this variation was attributed to fluctuations of instrumental pressure.

Response to Sample Vapors of Ketones

Chemical vapors which form product ions through favorable ionization properties as shown in Equation (1) provide a broad measure of peak separation and ion characterization through a range of reduced mobility coefficients:



where M is a sample molecule and the product ion, $\text{MH}^+(\text{H}_2\text{O})_{x-n}$, is termed a protonated monomer, and x is governed by moisture and temperature and n is governed by the enthalpy of associations. This reaction can be associated to proton affinities and ketones have comparatively strong values at ≥ 812 kJ/mole^[38] and provide uncomplicated ionization chemistry yielding mobility spectra characterized by symmetrical and resolvable peaks.^[39] The product ions are long-lived and spectra are free of secondary ion-molecule reactions in the drift region. Also, ketones have been successfully used to characterize response of mobility spectrometers and a history of response with documentation is available.^[40] An additional benefit for ketones is the concentration dependent response with the formation of proton bound dimers as shown in Equation (2):



Mobility spectra of ketones are shown in Figure 5 for representative samples of 2-pentanone, 2-heptanone and 2-nonanone obtained for each chemical throughout a range of concentrations are overlaid in the figures so any anomalies in drift time with concentration could be observed. This can occur with ketones when vapors of sample are allowed to penetrate the ion shutter and enter the drift region and ion identities, as seen in extent of clustering of ions with sample vapor, become dependent upon vapor concentrations. Spectra contained reactant ions peaks, protonated monomers, and proton bound dimers which showed constant drift times regards of concentration and consequently, constant mobility coefficients. This should occur in a drift tube that is well-designed and operated analyzer and results here demonstrate that drift tube functioned as intended.

Drift times for the product ions of ketones spanned the range from ~ 9 to 18 ms as listed in Table 1 and reduced mobility coefficients (K_0) were calculated for the same ions using a method of reference to a chemical standard, here 2,4-dimethylpyridine.^[41] The smallest ion was the protonated monomer of 2-propanone (59 amu) with a drift time t_d of 9.3 ms and the largest ion was the proton-bound dimer of 2-nonanone (143 amu) at 17.5 ms. The corresponding K_0 values were $2.1 \text{ cm}^2/\text{Vs}$ and $1.1 \text{ cm}^2/\text{Vs}$, respectively. Reduced mobility coefficients should be comparable between analyzers and results from the planar drift tube were compared to

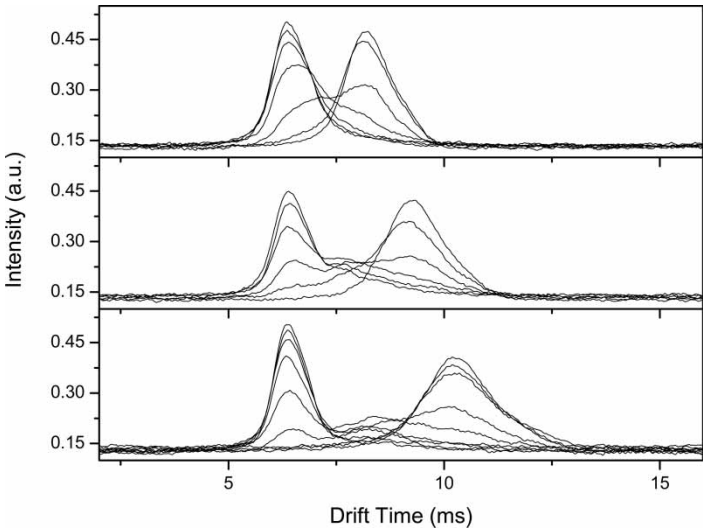


Figure 5. Mobility spectra for 2-pentanone, 2-heptanone and 2-nonanone with planar drift region equipped with ^{63}Ni ion source. Spectra obtained in air at ambient pressure with 300 μs pulse width for the ion shutter.

those from a conventional cylindrical drift tube with comparable chemical standard.^[42] Further, comparisons should be possible since both experiments were completed near room temperature in a supporting gas of air at low moisture. As shown in Figure 6, the K_o values from the planar drift tube are

Table 1. Values obtained from mobility spectra of individual chemicals in a homologous series

Chemical	Drift time (ms)			Reduced mobility (cm^2/Vs)	
	Reactant ion peak	Protonated monomer	Proton bound dimer	Protonated monomer	Proton bound dimer
2-Propanone	9.28	9.28	10.48	2.14	1.89
2-Butanone	9.27	9.85	11.67	2.01	1.70
2-Pentanone	9.24	10.48	12.87	1.89	1.54
2-Hexanone	9.24	11.09	14.03	1.79	1.41
2-Heptanone	9.27	11.82	15.30	1.69	1.30
2-Octanone	9.24	12.51	16.42	1.60	1.21
2-Nonanone	9.25	13.18	17.51	1.52	1.13
Chemical standard 2,4-Lutidine	9.22	10.16	13.82	1.95	1.43

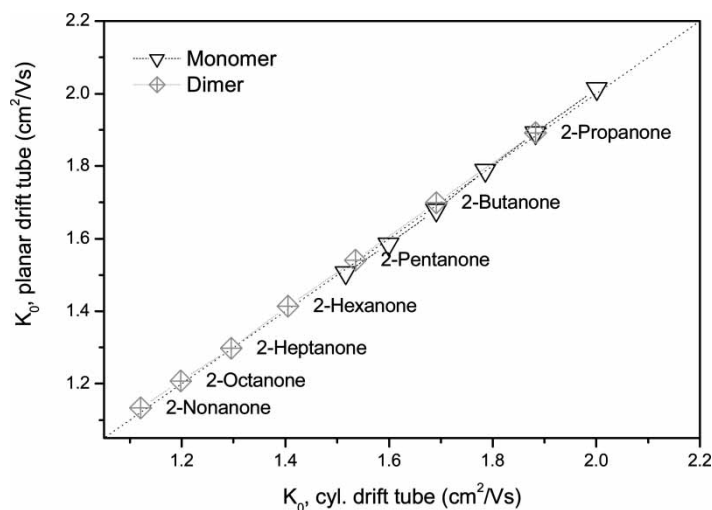
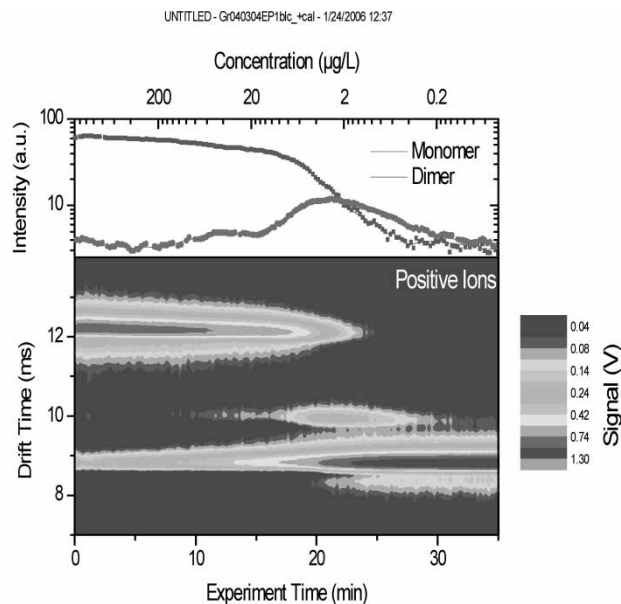


Figure 6. Reduced mobilities coefficients from ketones in a series from 2-propanone to 2-nonanone from a planar drift tube and a cylindrical drift tube. The dotted line is for an ideal correlation without error.

plotted against those from the cylindrical design and a dotted bisecting line marks identical K_0 values for both designs. All K_0 values were near this bisecting line, for all the monomers and dimers of the ketones measured, and the average difference of K_0 values was smaller than 0.6%. These findings illustrate that the behavior of ions in the planar drift tube showed no mass bias or mobility bias and the analyzer functioned in a regular manner.

Response to Sample Vapors Concentrations

The patterns of peak intensity for reactant ions, protonated monomers, and proton bound dimers, with changing concentrations of sample vapor, are useful diagnostics of drift tube performance and provide a measure of memory effects. An exponential dilution experiment provided response to a range of concentrations, for example, from 30 ng/L to 900 $\mu\text{g/L}$ of 2-pentanone in air. Results for peak intensities from positive ion mobility spectra obtained throughout the changing concentrations are shown in Figure 7 as a topographic plot with a logarithmic scale on the intensity axis. Analyte concentrations were calculated under the assumption of a known initial analyte amount which was diluted exponentially by clean air. At the beginning of the experiment, maximum concentrations of vapors were introduced into the analyzer and this was seen as a pronounced peak for the proton bound dimer (see Equation (2)). As the vapor level decreased with the dilution



⁶³Ni-Planar-IMS of 2-Pentanone in Air from 040304 (2nd run)

Figure 7. Plots of peak intensity for protonated monomer and proton bound dimer for 2-pentanone in exponential dilution experiment with planar drift region (top). Mobility spectra can be seen in topographic plot of the same experiment (bottom).

process, intensities for both the protonated monomer and the reactant ion peaks grew. With further dilution of the sample, the peak for the protonated monomer decreased (see Equation (1)) until only the reactant ion peak was observed with a vapor level below that of the detection limit. The limit of detection for 2-pentanone using the planar drift tube was determined as ~ 60 ng/L which is slightly higher than reported for mobility spectrometers using cylindrical designs.^[43] This was attributed to poor source and reaction region designs and this could be seen in the dynamics of ion intensities.

The appearance of a reactant ion peak and the proton bound dimer peak together as shown in Figure 7 is not usually observed with mobility spectrometers and could be attributed to unconventional ion source design and absence of a significant reaction region. The ion source was placed in a tube union and attached to the wall of the analyzer. This meant that sample vapor was exhausted through the source with residence times of 0.2 ms and that no additional mixing or contact between ions and sample neutral occurred as common to reaction regions of drift tubes. Worse still, the flow dynamics in the union were unknown and the existence of proton bound dimer and reactant ions together meant that the source region was a limitation on the overall performance of the drift tube. Thus, detection limits and other

quantitative performance should be regarded as preliminary as no part of this analyzer was optimized for either resolution or detection limits in this first demonstration.

Alternate Ion Sources

Although the ion source design of Figures 1 and 2 was not optimized for detection limits, an advantage was flexibility-any method of forming ions in air at ambient pressure could be easily adapted to the drift tube and this was demonstrated here with a photo-discharge lamp. Ultra-violet ionization is an alternative to radioactive ion sources in IMS^[44–47] and atmospheric pressure photo-ionization has recently garnered interest with liquid chromatography-mass spectrometry methods.^[48] Selected ketones from Table 1 were characterized using a planar drift tube equipped with a 10.6 eV photo-discharge lamp which was placed at the end of the drift tube in place of the union which contained the radioactive source. The ionization energies of ketones favor ionization with ionization energies between 9.7 eV for 2-propanone and 9.3 eV for 2-heptanone.^[38] Although drift times were not directly comparable to those in Table 1 since the electric field was altered by increase length of drift region and a modified voltage divider, the drift time increases with increasing analyte ion mass from 10.27 ms (2-propanone) to 11.45 ms (2-butanone) and 12.60 ms (2-pentanone). The identity of the ion was not determined here; however, proton bound dimers have been mass identified previously with the photo-ionization of ketones in air.^[49] Results here do not support proton based reaction chemistry since the patterns here lacked either a reactant ion (which can be seen with proton mediated chemistry following photoionization) and a protonated monomer at low vapor concentrations. Therefore, a tentative interpretation is that the ions in Figure 8 were formed through charge exchange reactions. Likely possibilities, pending mass analysis, include M^+ and clusters of M^+ .

Analysis of Fabrication Costs

The production of a single set of circuit boards by a commercial vendor with photolithography was \$35 and consumed ~1 hour of design time. The entire assembly was possible in under an hour and total production costs with skilled labor should be perhaps \$200 with labor and benefits for a total cost of under \$250. In contrast, the machine shop charge for a drift tube alone is \$1000 from precision machining of rings over several days. The time for assembly of such a drift tube is ~4 hours making the cost of a research grade conventional analyzer near \$2000, perhaps an order of magnitude more than the planar design. Such comparisons will need modification when the circuit board is replaced with a ceramic or glass substrate; however, the expenses are

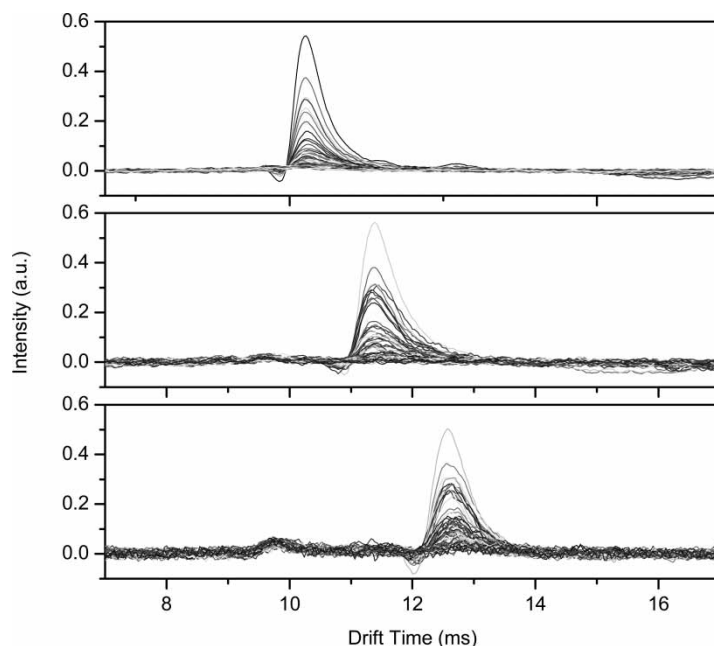


Figure 8. Mobility spectra of 2-propanone, 2-butanone and 2-pentanone using a planar drift tube UV-mobility spectrometer.

strongly weighted in favor of a planar configuration even a 2x or 3x increase in costs for the planar material with high temperature compatibility. Cooling of the voltage divider or use of fire resistant resistors when drift tube temperatures exceed 100°C will add cost to these calculations.

CONCLUSION

A planar drift tube for an ion mobility spectrometer exhibited behavior consistent with that of drift tubes of conventional cylindrical geometries and the original intention, to simplify the design and fabrication of mobility analyzers, was fulfilled. The signal intensity was approximately that of existing drift tubes in the same laboratory and the response to ketones showed no unusual behavior. The present design was provided spectral profiles and reduced mobility coefficients compared favorably with conventional designs, mindful of the inefficient ion shutter. Detection limits in this prototype unit were 10 to 100 fold higher than refined conventional tubes though this was though associated with low residence times of the vapor in the ion source or reaction region. The modular and planar design philosophy is expected to allow convenient modification of sizes and shapes of an

analyzer through replacement only of a few components, the plates containing the metal drift plates, insulating rails, and drift tube brackets.

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