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Characterization and optimization of membrane inlets for a miniature ion trap mass spectrometer operating at a high background pressure of humid air

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ABSTRACT

A 10-kg handheld ion trap mass spectrometer, the Mini10, operating at a high background pressure (10^{-4} Torr range) of humid air was characterized and optimized with respect to the use of membrane inlets. Both flat sheet and tubular membrane inlet configurations in different dimensions were tested using aqueous solutions and inlet temperatures ranging from 25 to 90 °C. The results show that both the absolute ion abundances and the relative abundance of ions in the recorded spectra of volatile organic compounds were highly influenced by the pressure in the vacuum chamber. At elevated pressures the signal intensities dropped, and a shift from primarily electron ionization to primarily chemical ionization was observed. For some chemicals unexpected high-intensity water adduct ions were observed, as confirmed by MS/MS experiments. The pressure effects were found to be correlated with the ionization potential of the analytes, the higher the ionization potential the stronger the effects. Since the pressure in the vacuum chamber is determined by both the membrane dimensions and the temperature of the inlet, the optimization of the membrane inlet is a matter of balancing membrane dimensions and inlet temperature such that both a maximal intensity and an acceptable short response time are achieved simultaneously. In contrast to what is observed for benchtop instruments, elevated inlet temperatures may lead to reduced signal intensity, and the use of a thicker membrane may increase signal intensity. Under all circumstances we found that a linear relationship between signal intensity and sample concentration was observed over at least two orders of magnitude as long as the operational conditions of the system was kept constant. The pressure effects described here are likely to be general for all miniature ion trap mass spectrometers using low performance vacuum pumps.

1. Introduction

Currently significant development is going on in the field of miniaturization of mass spectrometers in order to make mobile or even handheld mass spectrometers [1–7]. Such mobile mass spectrometers open for the use of on-site measurements in the environment with a number of advantages compared to measurements performed in the laboratory [8]. The most important advantage is probably the near real time data information that allows almost immediate action to be taken in connection with surveillance tasks, and sampling strategies can be altered on-site based upon the acquired information. Furthermore, on-site analysis reduces the possibility of altered sample composition as a result of transportation and storage.

Mass spectrometry has clear advantages compared to other analytical on-site techniques with its relatively high selectivity, in particular when it is used together with gas chromatography. Commercially available portable GC/MS systems are available from several companies such as Inficon, Griffin Analytical Technologies, Torion Technologies and Microsaic Systems. An example of a typical application of field portable GC/MS is the analysis of mustard and nerve gases [9]. An alternative to the use of GC/MS for high selectivity is MS/MS, and recent developments in ion trap technology have made MS/MS available for field portable instruments [10,11]. Typical inlets used with field portable mass spectrometers are capillary inlet systems and membrane inlets. For example, the contents of unidentified cylinders and barrels from World War II have been analyzed on-site using a capillary inlet [12], and membrane inlets have been used in the field with applications such as continuous measurement of volatile organic-chemicals in natural-waters [13] and in underwater mass spectrometers for in situ chemical analysis of the hydrosphere [14]. Very low detection limits have been obtained (800 ppt) for volatile organic compounds in air with a handheld mass spectrometer using a sorbent tube for pre-concentration prior to analysis [15].

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Membrane inlet mass spectrometry (MIMS) [16–18] is probably the most versatile inlet for use in the field, and complete membrane inlet mass spectrometers with a weight at or below 10 kg, everything included, have recently been developed [10,19,20]. The main advantages of MIMS are the simplicity of the design, selective introduction of volatile organic compounds and the ability to perform on-line monitoring of both air and water samples. When membrane inlets are used together with a miniaturized instrument the operational conditions are not similar to those used with small benchtop instruments. The vacuum pumps have a smaller pumping capacity, and the end pressure in the vacuum chamber (no inlet) is much higher, typically 1×10^{-5} Torr range. This high pressure of humid air inside the vacuum chamber can influence the characteristics of the instrument. Miniaturized ion traps that use longer trapping times in order to compensate for lower sensitivity could be expected to be even more sensitive to the high background pressure of air.

In the present study we have worked with the Mini10 mass spectrometer [10], which is a 10-kg mass spectrometer with a rectilinear ion trap [21] analyzer and electron ionization taking place in-side the ion trap. We have tested the instrument for analysis of aqueous solutions with membrane inlets using both flat sheet and tubular silicone membranes in varying dimensions and operated at temperatures from 30 to 90 °C. The paper will demonstrate that its characteristics are very different from those observed with standard membrane inlet systems using benchtop mass spectrometers.

2. Experimental

2.1. Instrumentation

The mass spectrometer used in this work was the Mini10 [10], developed by Cooks and coworkers at Purdue University, USA. The Mini10 is a 10-kg mass spectrometer using a rectilinear ion trap as mass analyzer. It has the facility of electron ionization (EI) with a filament producing electrons that are guided into the ion trap where the ionization takes place. The filament, the ion trap and the detector (an electron multiplier) are located next to each other, and molecules are ionized with EI simply by letting them into the vacuum chamber (for example through a membrane or a capillary leak); eventually they diffuse into the ion trap where they get ionized, trapped and analyzed. Of particular interest for this paper is the small pumping system used, a TPD011 Compact-Turbo drag pump (Pfeiffer Vacuum, Asslar, Germany) backed by a small diaphragm pump (model no. 1091-N84.0-8.99, KNF Neuberger, Freiburg, Germany), which has an ultimate pressure just below 1×10^{-5} Torr with the vacuum system sealed off. The pressure was monitored with a micro-Pirani vacuum gauge (MKS 925C, MKS Instruments, Inc. Wilmington, MA) capable of measuring the pressure from 1×10^{-5} Torr and up. Schematic drawings of the Mini10 can be found in the original paper [10].

For this study a number of membrane inlets were constructed using both a flat sheet and tubular membrane configuration (see Fig. 1). The membrane inlets were mounted directly on the vacuum chamber of the Mini10. The tubular membrane inlets were of the original design, except that different lengths of tubing were used, and the flat sheet inlets were of the flow through type [22] with exposed membrane areas of 7 mm^2 (circular ∅ 3 mm) and 79 mm^2 (∅ 10 mm). The flat sheet inlets used membranes of thicknesses 51, 127 and 254 μm, and the dimensions of the tubular membrane were 0.635 mm i.d. and 1.19 mm o.d. (thickness 275 μm). In all cases the membrane material was made of poly-dimethylsiloxane (Technical Products, Inc, GA).

A small peristaltic pump (1 mL/min, model 101-005-012-030/4, Williamson Manufacturing Co. Ltd, West Sussex, UK) powered by a built-in 12-V relay of the Mini10 was used to pump the sample solution through the inlet. Electrical thermostating of the membrane inlet was obtained using a small temperature controller (CN132, Omega Engineering Inc., Stamford, CT), a thermocouple (5-TC, Omega Engineering Inc.) and a cartridge heater (24 V, 25 W, 1 in. length, 1/8 in. diameter, Watlow Ltd., Nottingham, UK). Power for the temperature control system was obtained from the same 24 V power supply or battery pack that powers the Mini10 itself. Using this setup the temperature of the membrane could be stabilized within ±3 °C. For normal operation of the membrane inlet this setup is sufficient. However, for the measurements presented here, where a precise temperature control was needed, an external power supply was used to pass a constant current through the heating cartridge providing steady temperatures, and the temperature controller was only used as a monitor. In this fashion we stabilized the temperature within ±0.5 °C. For the flat sheet inlets the aluminum block fixing the membrane was heated, thus providing heating of the liquid going in, and in the tubular setup the heating took place via an aluminum cylinder attached to the stainless steel tube leading the liquid into the membrane. The pumping speed, 1 mL/min, provided sufficient time for the liquid to reach the right temperature.

2.2. Ion trap operational parameters

A scan function was created with a low mass cutoff of *m/z* 50 and a scan range up to *m/z* 200 (with the instrument's default rf frequency of 1 MHz). Resonance ejection was performed at 350 kHz with an AC ramp from 0.15 to 0.45 V, providing unit resolution in the entire scan range. The ionization time was 50 ms, followed by 10 ms of ion cooling and acquisition over 50 ms.

2.3. Chemicals

All chemicals (acetophenone, benzaldehyde, chloroform, methyl salicylate and benzaldehyde) were purchased from Sigma–Aldrich, and MilliQ water from a Millipore system was used for dilution.

3. Results and discussion

3.1. Effect of background pressure upon sensitivity and appearance of the mass spectra

A number of compounds (acetophenone (recorded at *m/z* 105), benzaldehyde (*m/z* 105), chloroform (*m/z* 83), methyl salicylate (*m/z* 152) and toluene (*m/z* 91)) in concentrations of approximately 5 ppm in water were investigated with a 36-mm long tubular membrane inlet. Two of the compounds, having no spectral interferences, were measured in a mixed solution, the rest of the compounds as pure solutions of one compound at a time. The signals from their peaks were monitored as the membrane temperature was gradually ramped from 25 to 90 °C over 30 min. As a result of the increasing membrane temperature analyte molecules as well as water and air will permeate the membrane to a higher extent, resulting in increased partial pressures and total pressure inside the vacuum chamber [23]. During the experiment the pressure inside the vacuum chamber was observed to rise from 1×10^{-4} to 4×10^{-4} Torr.

Fig. 2 shows the result of the experiment with signal intensities normalized for each compound, such that it has a maximum measured intensity of 100. In contrast to expectations the intensity of the ions does not increase with temperature as normally

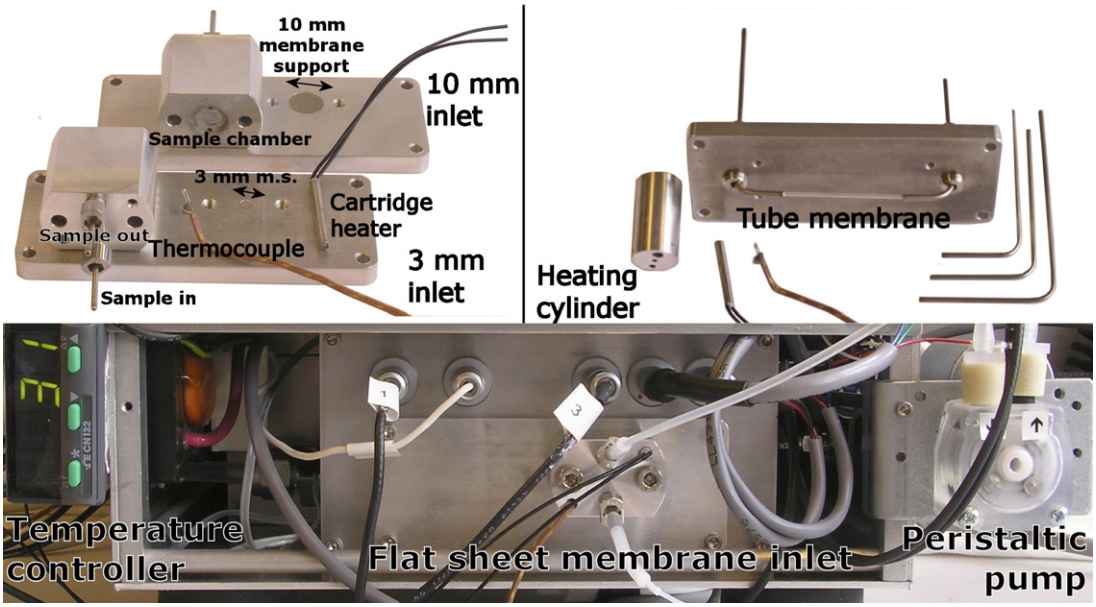

Fig. 1. Top: The flat sheet membrane inlets and the tubular membrane inlet. The three bent metal tubes allow for other lengths of the tubular membrane. Bottom: The vacuum chamber of the Mini10 with the ∅ 3-mm flat sheet membrane inlet mounted. The temperature control and the peristaltic pump are integrated parts of the instrument and do not add significantly to the weight of 10 kg.

observed [24] when aqueous samples are analyzed for volatile organic compounds using MIMS. Instead a reduction (chloroform, benzaldehyde and acetophenone), an initial increase followed by a reduction (toluene) or an almost constant intensity (methyl salicylate) was observed. The effect was reversible such that the signal would return to its previous intensity upon cooling of the membrane inlet. Methyl salicylate, toluene, acetophenone, benzaldehyde and chloroform have ionization potentials of respectively 7.65, 8.83, 9.28, 9.50 and 11.37 eV [25], and apparently the higher the ionization potential the stronger the temperature/pressure effect is. To test whether the ionization process had something to do with the observation the experiment was repeated with different emission currents, and we observed that the effect was reduced with increasing emission current. The data shown in Fig. 2 were recorded using a slightly higher filament voltage than what is normal for the Mini10.

For all membranes the vacuum chamber pressure was below 1×10^{-5} Torr when the membranes were just exposed to air or other gases, while it rose to up to 1×10^{-4} Torr (and even higher at elevated temperatures) when aqueous solutions were flushed though the inlet. It is thus conceivable that in particular water contributes very much to the increased pressure, and water molecules in the vacuum chamber appear to have consequences for the analyte molecules. Fig. 3 shows four different spectra of benzaldehyde:

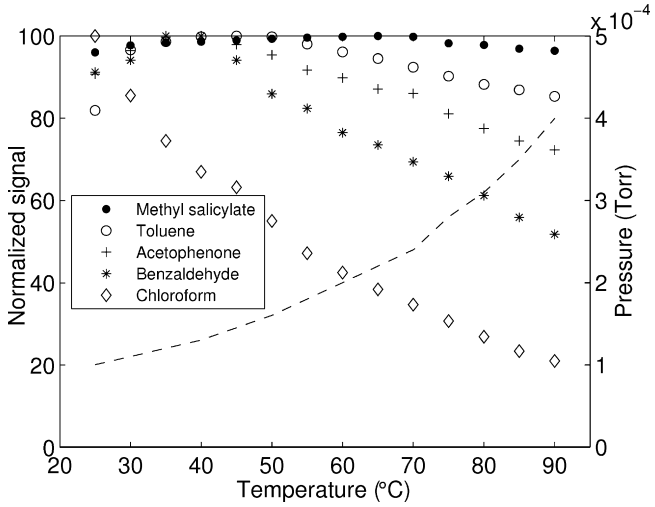

Fig. 2. The signal intensities of five compounds monitored as the temperature is steadily ramped over approximately 30 min. The signal intensities of the base peaks (methyl salicylate: *m/z* 152; toluene: *m/z* 91; acetophenone: *m/z* 105; benzaldehyde: *m/z* 105; chloroform: *m/z* 83) are normalized for each compound relative to the temperature that provides the highest signal intensity. The dashed line shows the pressure in the vacuum chamber at different temperatures (right axis applies).

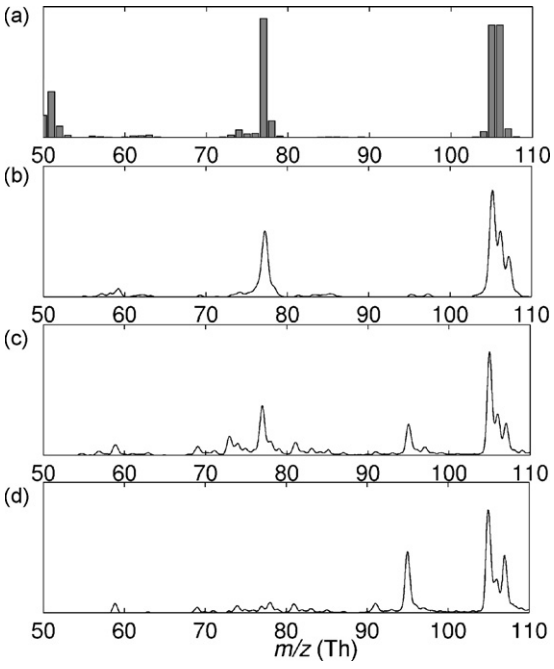

Fig. 3. Mass spectra of benzaldehyde. (a) Standard EI spectrum from the NIST database [25]; (b) from headspace; (c) from aqueous solution at 25 °C; (d) from aqueous solution at 90 °C.

the standard spectrum from the NIST database [25], a gas phase spectrum recorded from the head space (also with a membrane inlet on the Mini10), and two spectra of a 10-ppm aqueous solution recorded at 25 and 90 °C, respectively. The gas phase spectrum (b) shows some degree of chemical ionization (CI) when compared to the pure EI spectrum in (a): the molecular peak at 106 is diminished, and the [M+1] peak at *m/z* 107 has grown. In the spectra of aqueous solutions (c, d) we see the emergence of a new peak at *m/z* 95, whose origin is not immediately evident. At higher temperatures this peak grows at the expense of the peak at *m/z* 77, which disappears completely at 90 °C. The development of the different peaks in the spectra as the temperature is ramped from 30 to 90 °C is shown in Fig. 4. The three main peaks in the EI spectrum at *m/z* 77, *m/z* 105 and *m/z* 106 are all decreasing, while the new peak at *m/z* 95 and the [M+1] peak at *m/z* 107 are unaffected, if not actually increasing. The sum of all the peaks has been calculated and plotted over the temperature range in order to show that the total ion intensity follows that of the base peak and is decreasing with higher temperature and pressure (the same behavior was observed for the other compounds in Fig. 2 where, for simplicity, only the intensities of the base peaks in the spectra were plotted).

To confirm that the *m/z* 95 peak was indeed coming from benzaldehyde an MS/MS experiment was made on the *m/z* 105 base peak of benzaldehyde. The resulting spectrum is shown in Fig. 5 and clearly demonstrates that the *m/z* 95 peak originates from the *m/z* 105 peak. An MS/MS experiment performed on the *m/z* 95 peak itself revealed that this ion was a water adduct of the phenyl ion at *m/z* 77. The behavior described here was also observed for methyl salicylate. In this case an unusual peak at *m/z* 138 is present. This ion originates from a water adduct to the electron ionization base peak ion of methyl salicylate at *m/z* 120 (the M+ ion minus a loss of MeOH). Just like benzaldehyde, methyl salicylate also shows high-intensity protonated ions at *m/z* 153 ([M+1]+) and *m/z* 121 ([M+1–32]+).

The experiments described above show that when a Mini10 is used for water analysis using a membrane inlet, the recorded mass spectra will be a mixture of electron ionization and chemical ionization. The decisive parameter is the pressure inside the vacuum chamber. When the pressure increases from approximately 1×10^{-4} to 6×10^{-4} Torr a shift from primarily electron ionization to primarily chemical ionization is observed, and new ions appear as a result of gas phase reactions between analyte and water molecules and ions.

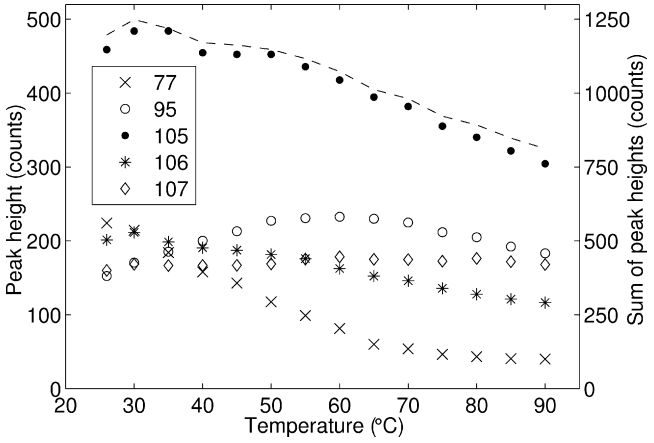

Fig. 4. Plot of the transition between (Fig. 3c and d), showing the intensities of the peaks throughout the temperature range. The dashed line shows the sum of the peak heights (right axis applies).

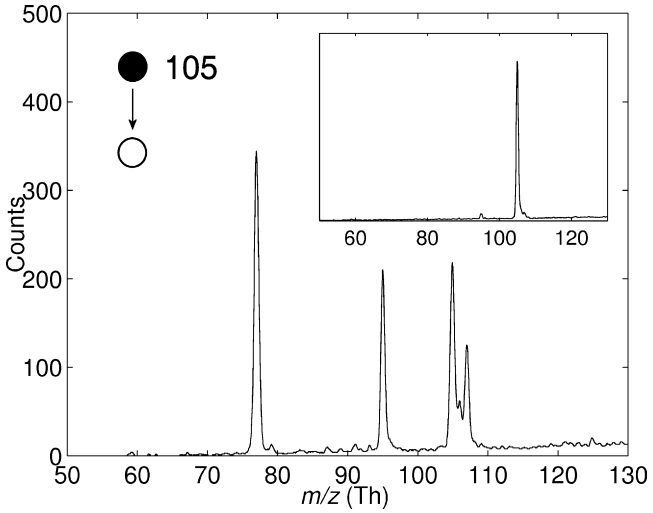

Fig. 5. The MS/MS spectrum of the 105 Th peak of the aqueous solution of benzaldehyde. The insert shows the isolated 105 Th peak prior to the CID (collision induced dissociation) step.

3.2. Influence of membrane inlet parameters

From the observations described above it is clear that the pressure in the vacuum chamber has a critical impact on ion abundances and thus the sensitivity of the instrument. The pressure in the vacuum chamber depends upon both the membrane temperature and the membrane dimensions. Contributing to a higher pressure and thus a degraded sensitivity are the following: large membrane areas, thin membranes and high membrane temperature. The same factors also promote the transport of analyte molecules through the membrane and thereby increase their partial pressures inside the vacuum chamber. We thus have two effects working in opposite directions, and the challenge is to balance these two effects in order to maximize the sensitivity. On top of that we find another factor that needs to be considered simultaneously with sensitivity, the membrane response time. Short response times are favored by thin membranes and high temperatures, thereby counteracting the desire for high sensitivity.

To investigate the influence of the three membrane parameters, area, thickness and temperature, we selected one compound, benzaldehyde, which can be considered an average of the compounds in Fig. 2; it shows the discussed effects, but not to the extreme extent as chloroform does. Fig. 6 shows the detected signal from *m/z* 105 and the measured pressure in the vacuum chamber as a function of temperature for tubular membrane inlets with length of 9, 19, 27 and 36 mm. We see that the pressure increases dramatically with the length of the membrane, and the relative loss of signal due to heating is much higher for the larger membranes than for the smaller, simply because of a higher increase in pressure caused by the heating. Still, the long membrane of 36 mm comes out as the best one from the perspective of maximal signal at all temperatures. However, the pressure in the vacuum chamber stays low (<1×10^{-4} Torr) up to approximately 70 °C with the short membranes making it possible to work with almost clean electron ionization and with short response times (see below). For the two shortest membranes the signals are comparable in intensities. We believe that for this particular combination the higher intake of analyte molecules for the longer membrane is counteracted by the accompanying pressure effect.

Fig. 7 shows principally the same as Fig. 6, but this time with flat sheet membranes using two diameters, 3 mm (7 mm^2 area) and 10 mm (79 mm^2 area) and three different thicknesses 51, 127 and

Table 1
The response times in seconds ($T_{10–90\%}$) for benzaldehyde determined at different temperatures for different types of membranes

	Temperature (°C)		
	40	60	90
51-μm flat sheet	60	36	16
127-μm flat sheet	78	48	33
254-μm flat sheet	160	105	55
Tubular, 275-μm walls	130	70	34

254 μm. At low temperatures the 10-mm inlet gives higher intensities than the 3-mm inlet, but going to higher temperatures the situation turns around, and the best signals are observed with the small membrane. For the 10-mm inlet we observe the – in a MIMS context – highly surprising result that the thick membrane gives higher intensities than the thinner membrane, simply because the pressure in the vacuum chamber is lower; we have exceeded the pressure where the higher intake of analyte molecules can compensate for the accompanying pressure effect. For the 3-mm membrane the behavior of the inlet is almost as expected for membrane inlets, the signal increases with temperature (apart from the thin membrane that reaches a maximum at 60 °C) and the thin membranes give the highest intensity.

The response times of all three flat sheet membranes as well as the tubular membranes were measured at three different temperatures, and the results are shown in Table 1. We see that there is a significant difference in the response time between the thinner flat sheet membranes and the tubular membrane, and heating

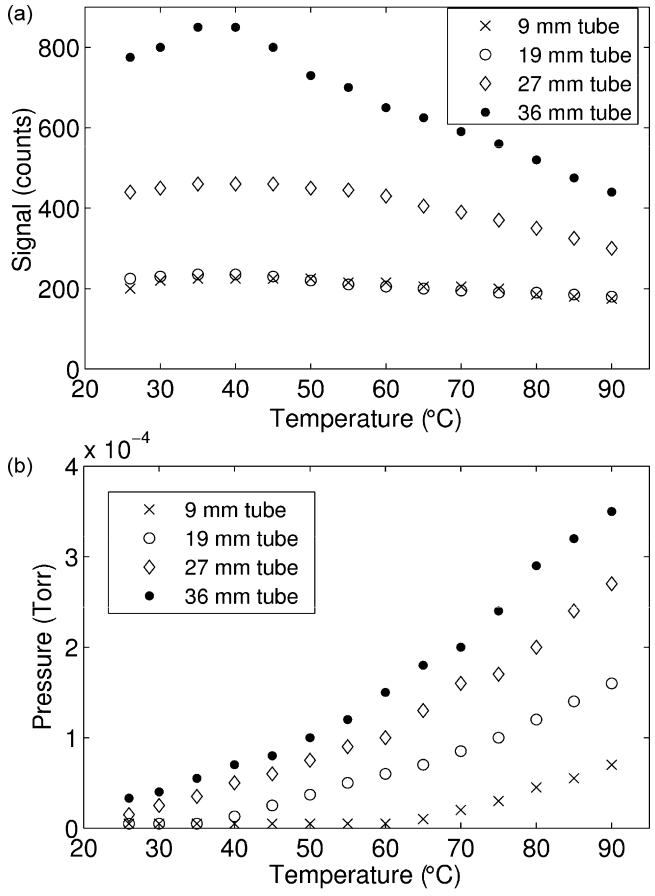

Fig. 6. (a) The intensity of the *m/z* 105 peak of a 10-ppm benzaldehyde solution as a function of temperature for a number of different tubular membrane lengths. (b) The pressure in the vacuum chamber during the measurements.

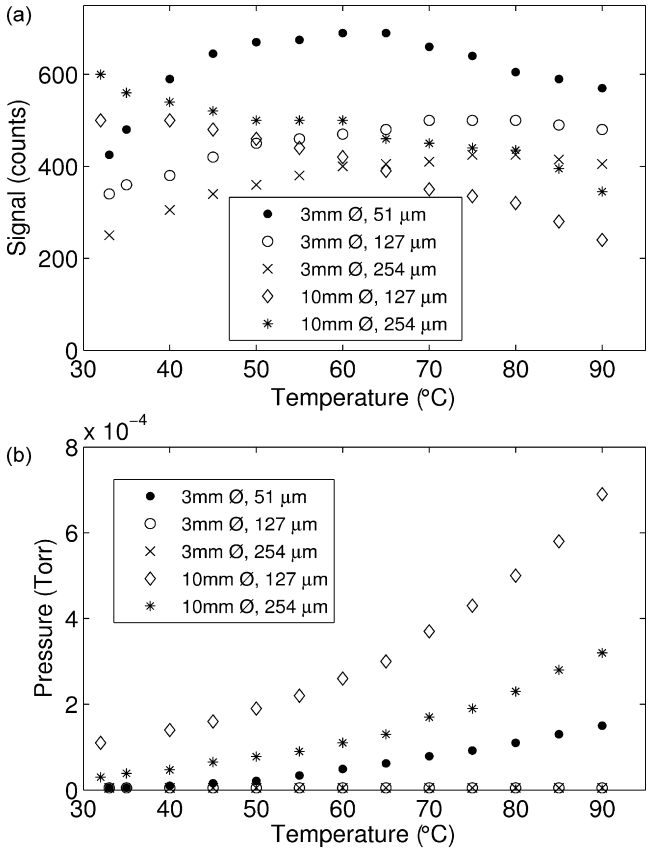

Fig. 7. (a) The intensity of the *m/z* 105 peak of a 10 ppm benzaldehyde solution as a function of temperature for a number of different flat sheet membrane configurations. (b) The pressure in the vacuum chamber during the measurements.

is needed in order to obtain reasonable response times with the tubular membrane. Without heating the tubular membrane has response times of several minutes.

3.3. Quantitative aspects

Choosing the two optimal membrane configurations, the 36-mm tubular membrane, and the 3-mm flat sheet with a 51-μm membrane, we made a number of calibration curves in order to test whether the pressure effects discussed above had an influence upon the linearity of the instrument. With both membrane inlets operating at temperatures ranging from 30 to 80 °C we always obtained linear calibration curves over 2–3 orders of magnitude with correlation coefficients near 0.99 in the case of benzaldehyde. The best detection limits for benzaldehyde were found to be 100 ppb at 40 and 60 °C using the flat sheet membrane, whereas it was 50 ppb at 40 °C using the tubular membrane. The reason that the same limits of detection were found for two different temperatures is that for these measurements the filament voltage was set to be very high (in order to boost the sensitivity), and the pressure effect was therefore less pronounced. The Mini10 has the possibility of isolating ions using the SWIFT technology [26] and by isolating *m/z* 105, we managed to lower the detection limit to 20 ppb with the flat sheet membrane. The limits of detection we have found for benzaldehyde compare quite well with the 50 ppb detection limit that was reported for aqueous solutions of naphthalene in the first paper about the Mini10 [10], using the same tubular membrane, though at a much higher flow rate (20 mL/min) and without heating.

Whether to prefer one membrane configuration to the other is to some extent an open question. The 36-mm tubular membrane has the lowest detection limit for benzaldehyde, but this advantage has at a significant cost in the form of a prolonged response time as compared to the 3-mm flat sheet membrane, and since the 36-mm tubular membrane operates at a much higher pressure the mass spectra recorded are intermediary between electron ionization and chemical ionization. The five compounds tested in this work (see Fig. 2) are affected to different extent by the background pressure, and the optimal membrane inlet is not necessarily the same for all compounds.

One might argue that performance might be gained by optimizing the ion trap scan function (in particular with respect to the resonance ejection AC amplitudes) when the pressure changes. It is true that some performance is gained in this way (higher AC amplitudes are needed at higher pressures). However, this far from accounts for the pressure effects we are observing over a – in spite of everything – limited pressure range. Even when the scan function is optimized at higher pressures the sensitivity of chloroform is still much lower than that of benzaldehyde, in contrast to what is observed with MIMS on benchtop instruments.

3.4. Influence of ion/molecule reactions

We have seen (cf. Fig. 3c and d) that the appearance of the mass spectra are highly influenced by the background pressure of humid air with a considerable extent of ion molecule reactions taking place. With the Mini10 we typically use an ionization time of about 50 ms, and going lower than 25 ms gives too low intensity. The 50 ms of ionization leaves the ions plenty of time to react. That reactions are indeed going on in that time is seen by the fact that protonated benzaldehyde (*m/z* 107) is greatly enhanced, when longer ionization times or cooling times are chosen, i.e., proton transfer is promoted by longer trapping times. By setting the ionization time to 200 ms and the cooling time to 200 ms we are even able to make the *m/z* 107 peak larger than the *m/z* 105 peak. MS/MS experiments have also shown that unexpected water adduct ions may appear in the spectra. For example benzaldehyde produces a very intense ion at *m/z* 95 from a water adduct of the phenyl ring.

Charge exchange reactions can also occur while the ions are trapped, i.e., analyte molecules that have been ionized may pass on their charge to background molecules (water and air) while they are trapped. This would explain why molecules with high ionization potentials are more vulnerable to the pressure effects than molecules with low ionization potentials. Their ions are simply neutralized by extracting an electron from the molecules in the vacuum background gas. An observation that supports this theory is that argon (with ionization potential 15.76 eV) does not show up in a standard air spectrum with the MIMS on the Mini10 instrument, neither does it show up when the membrane is exposed to 10% argon gas in nitrogen. However, when the membrane is exposed to pure argon gas, a peak appears at *m/z* 40. This indicates that the ion source is indeed capable of ionizing argon, but the charge is lost when other molecules are present to do charge exchange with argon. The same phenomenon is observed for nitrogen, although not to the same extent as for argon.

The reason that the described pressure effects are observed on our miniature ion trap mass spectrometer rather than on lab scale mass spectrometer is the limited pumping capacity of the 10-kg instrument. On a lab scale instrument with high performance vacuum pumps the operating pressure would not be in the 10^{-4} Torr range, but rather in the range of 10^{-7} to 10^{-6} Torr, although often with the option of operating around 1×10^{-4} Torr, as regulated by a helium back pressure. With helium as the background gas the pressure effects described here would definitely not be observed, since it has an ionization potential of 24.59 eV and therefore does not deliver electrons to neutralize positive ions in the trap. Furthermore, we only expect these effects to be observed on miniature ion trap instruments and not on, e.g., benchtop ion traps or miniature quadrupoles, since the trapping of the ions is a prerequisite to allow the ions the time to react. Benchtop ion trap instruments use much shorter trapping times than the miniature ion traps, and in quadrupole instruments the ions are mass analyzed almost instantly after ionization, and therefore the effect is not observed there [20].

4. Conclusions

We have found that a miniature ion trap mass spectrometer pumped by low performance vacuum pumps works differently with MIMS on aqueous solutions than does a benchtop instrument. In particular the higher background pressure of water and air causes a significant extent of ion molecule reactions and decrease the overall sensitivity. The effect appears to be correlated with the ionization potential of the analyte molecules; molecules with high ionization potentials are more vulnerable to high background pressures, probably because they after ionization are more prone to exchange their charge with neutrals such as water and air. Since the background pressure of water and air is a function of the membrane dimensions and the membrane temperature, the very same factors that determine the flux of analyte molecules into the instrument, the two counteracting effects must be balanced in the choice of membrane dimensions and temperature. Despite the high influence of background pressure upon the spectra recorded we do find a linear relationship between ion abundance and concentration over 2–3 orders of magnitude as long as the operational conditions are kept constant.

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