A micro gas preconcentrator with improved performance for pollution monitoring and explosives detection

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A MICRO GAS PRECONCENTRATOR WITH IMPROVED PERFORMANCE FOR POLLUTION MONITORING AND EXPLOSIVES DETECTION

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Abstract: This paper presents the optimization of a micro gas preconcentrator based on a micro-channel in porous and non-porous silicon filled with an adequate adsorbent. This micro gas preconcentrator is both applicable in the fields of atmospheric pollution monitoring (Volatil Organic Compounds-VOCs) and explosives detection (nitroaromatic compounds). Different designs of micro-devices and adsorbent materials have been investigated since these two parameters are of importance in the performances of the micro-device. The optimization of the device and its operation were driven by its future application in outdoor environments. Parameters such as the preconcentration factor, cycle time and the influence of the humidity were considered along the optimization process. As a result of this study, a preconcentrator with a total cycle time of 10 minutes and the use of single wall carbon nanotubes (SWCNTs) as adsorbent exhibits a good preconcentration factor for VOCs with a limited influence of the humidity. The benefits of using porous silicon

24   to modify the gas desorption kinetics are also investigated.

25

26   **KEYWORDS**

27   Gas preconcentrator, Micro-channel, Porous silicon, Carbon nanotubes, Adsorbent

28   **1. INTRODUCTION**

29   In miniaturization of physical analysis methods, preconcentration appears as the essential element for

30   improving both the sensitivity and the selectivity of these devices [1, 2, 3, 4, 5]. Thus, micro-preconcentrators find

31   their applications in various systems for gas analysis such as solid phase micro gas chromatography (μ-GC)

32   [6, 7, 8, 9, 10], ion mobility spectrometry (IMS) [11, 12, 13] and electronic nose (E-nose) [14, 15, 16, 17].

33   The use of detection systems based on the preconcentration is growing since the need to quantify very

34   low concentration is growing up as well as in the field of civil security as in agribusiness and healthcare. For

35   example, in the later, there is a demand of preconcentrators for medical diagnostics as addressed by Mr.

36   Cho Seong et al [17] and William A. Groves et al [18]. They have analyzed through a preconcentration system,

37   the air exhaled by a patient while knowing that the appearance of some gas molecules in exhaled air is

38   characteristic of the metabolism, thus the state of patient's health. The presence of some of these VOCs is

39   attributed to a definite disease; for example, alkanes, benzene derivatives o-toluidine and aniline are referred

40   to lung cancer, while acetone is linked to diabetes...

41   In the environmental field, it should be noted that the increasing of industrialization around some major

42   cities causes great vigilance in the monitoring environmental pollution and the prevention of disasters. Each

43   country, through an environmental quality agency, sets tolerance limits for some VOCs. For example, in

44   United States, the threshold for benzene is determined by the U.S. EPA (U.S. Environmental Protection

45   Agency) to 500ppb in ambient air and 5ppb in drinking water [19]. While in France, the limit is set by IFEN

46   (French Institute of Environment) to 10μg/m^3 [20]. These limits continuously being reviewed to lower levers

47   require the implementation of more performing detection equipments with a low detection limit and very short

48   sampling time.

49   The need to improve both the sensitivity and the selectivity of some detection systems has prompted

50   many laboratories to review the implementation of their gas pre-conditioning system. Thus, systems with

51 multiple stages of preconcentration were developed to reduce both the influence of water vapor and other

52 interfering gases such as alcohol derivatives [17, 21]. S. M. Cho et al [17] have implemented two-stage

53 preconcentrators filled with a hydrophobic adsorbent (carbotrap) allowing to reduce the influence of water

54 vapor in the analysis of human exhaled breath. There are also other multiple stages preconcentration

55 techniques based on the difference of desorption temperature between the two preconcentration units to

56 overcome the influence of other interfering gases upon detection as demonstrated by B. Alfeeli et al [21] in

57 their concept of cascaded micro-preconcentrator.

58 A new innovative process in the field of micro-preconcentration is the use of porous silicon. Indeed, the

59 use of porous silicon as a binding surface for filing adsorbent appears as a very attractive approach in the

60 development of miniaturized preconcentration because it offers the possibility to deposit by fluidic solution

61 various types of adsorbent while avoiding the problems of overpressure during the experiences.

62 In our previous study [22 23, 24], a gas pre-concentrator based on porous silicon micro-channels filled with

63 carbon nanopowders from a fluidic solution has been developed. The present work aims to improve the

64 performance of this device, with new approaches in the design as well as in the choice of adsorbent

65 materials and modes of operation. We have further investigated the contribution of porous silicon in the

66 adsorption and desorption phases since besides the increase of its specific surface area as reported in [26],

67 porous silicon when coupled with the adequate adsorbent can also modify the desorption kinetics of the

68 target gas.

69 Alternative absorbent materials such as carbon nanotubes and polymers, whose surface areas, pores-

70 size distributions, and structures can be varied to serve as conformal adsorbents, were evaluated for the

71 improvement of the performance of the preconcentrator [5].

72 The devices in this study have been developed targeting the preconcentration of benzene and

73 nitrobenzene which are representative gases for several types of applications relevant from atmospheric

74 pollution control to explosives detection.

2. EXPERIMENTAL

2.1. Adsorbent Materials

The choice of the adsorbent material is an important factor in the performance of a micro gas preconcentrator. The suitable adsorbent must have a strong affinity with the target gas, a low activation energy of desorption, a large adsorption capacity vis-à-vis of the target gas and finally a good binding of its particles on the preconcentrator substrate in order to avoid an evacuation of the deposited adsorbent under high gas flow which is harmful for the performance of the devices. The activation energy of the adsorbent is symbolized by its desorption temperature; while the adsorption capacity is linked to the specific area.

Therefore, four different adsorbents such as activated carbon, carbon nanotubes (Single Walled Carbon NanoTubes-SWCNTs, Multi Walled Carbon NanoTubes-MWCNTs) and Tenax polymer have been tested for the preconcentration of benzene and nitrobenzene in presence of humidity by using various techniques: BET (Brunauer, Teller and Emmett) method, Thermal Programmed Desorption (TPD) and applying them to micro-preconcentrator devices.

The BET method is a volumetric adsorption of gas point by point, which allows obtaining the complete isotherms (adsorption and desorption). These gas adsorption/desorption isotherms (Nitrogen, Argon, Krypton...) will permit the determination of the specific area and the adsorbent texture. The value of the specific area is obtained from the absorption isotherms of a gas at the liquid nitrogen temperature (77K). TPD technique is often used to discern the different desorption products of a given adsorbent after an adsorption phase. This technique consists in programming the desorption heating rate and selectively measuring the desorption products with a mass spectrometer. In some cases, the adsorption phase can be done in situ and the desorption heating rate is set to 100°C/min in order to make easier the discrimination of the various desorption products.

The carbon adsorbent used in this test has been activated by thermal process. The activation of carbon is an oxidizing reaction in order to release internal porosity created during the carbonization, to expand the pores, to create new micropores and to increase its specific area. This step must be controlled to avoid the total elimination of the carbon structure as the activation at high temperature (up to 900°C) under oxygen can cause the total disappearance of carbon structure. That is why we have done the activation of carbon

102   nanopowder at 500°C during 3 hours in presence of oxygen. All the others adsorbents materials were not

103   activated because this process was not needed due to of their specific area already higher.

104   **2.2. Preconcentrator**

105   Micro-devices with different designs have been fabricated (figure 1) by deep reactive ion etching (DRIE)

106   of silicon wafers using a thick photoresist mask. In the case of porous silicon channels, prior to the DRIE, a

107   silicon nitride film is deposited to act as a masking layer during the porous silicon formation. Then, for both

108   types, a 50 nm thick thermal oxide of is grown prior to their sealing with a glass cover by anodic bonding.

109   The different channels are designed with the necessity of having some pillars or walls within the channels in

110   order to control the powders deposition by fluidic solutions [23, 24]. The neutral microchannel is designed

111   without structures in the internal chamber while the zigzag design with channel system at inlet/outlet, mostly

112   used in this work, is made with "V" shaped structures in order to improve the flow distribution not only during

113   the adsorbent deposition but also during experiments.

114   The first micro-devices realized at the beginning of this study were made following two depths of etching.

115   The internal chamber etched at 120µm into the silicon contains parallel channels, either smooth or with the

116   "scales". In order to receive the metallic micro-capillaries of 350µm used as fluidic connectors, the inlet and

117   outlet of the device were etched to a depth of 325µm. But we faced a non-uniform distribution of flow (Figure

118   1) and overpressure during the experiments, which have been confirmed by some fluidic simulations done

119   under three hypotheses such as:

120   - The pressure is applied only in the entrance of the microdevice while the outlet is under atmospheric

121   pressure;

122   - No interaction between the substrate and the fluid except the friction forces;

123   - And the turbulence effect was not considered in this simulation model.

124   New micro-components were designed with a uniform depth of 325µm for both the inlet/outlet and the

125   internal chamber in order to compensate the overpressure observed on previous devices during tests. In

126   addition, inlet and outlet were fabricated with a channel system to promote a uniform distribution of fluid

127   unlike the old micro-components. Indeed, the latter did not have this channel system and we observed for

128   them a non-uniform distribution of flow when performing the fluidic simulation developed below.

129   This improvement in the design of the micro-channels was confirmed by series of simulation devoted to

130   new micro-devices which have pointed, on one hand, an improvement in the distribution of the gas flow with

131   the presence of channel system at the inlet/outlet of the micro-devices (Figure 1) and on other hand, a

132   reduction of pressure losses thanks to the uniform depth of 325µm through all the microchannel in this new

133   design.

134

135   **2.3. Adsorbent deposition**

136   The adsorbent insertion in micro-channels has been realized by two methods. The first one is a

137   deposition using a fluidic solution [24], and the second one consists to deposit the adsorbent in a paste form

138   before the sealing of the glass cover. The choice of the deposition method is closely related to the adsorbent

139   nature. According to dimension of the metallic capillary used as fluidic connection (220µm of internal

140   diameter), the first deposition method is more suitable for adsorbent materials with a particle size less than

141   5µm of external diameter. Thus, the activated carbon (100nm of particle size) and carbon nanotubes (CNTs)

142   were inserted in the microchannels by fluidic solution while Tenax TA was deposited in a paste form before

143   the sealing of the microdevices because of its large particle size close to 250µm.

144   These experiments on the fluidic deposition of the adsorbent have shown that the presence of pillars in

145   the preconcentration chamber, particularly in the "zigzag" design, is a key factor to homogenize the

146   distribution of the liquid flow through the entire device and to enhance the carbon deposition. It was observed

147   that the use of porous silicon has increased the quantity of deposited carbon in the micro-channels. In fact,

148   the presence of pores on the surface of the walls constitutes an important asset to get a good binding layer

149   and thus to increase the quantity of adsorbent filled in the micro-channel compared to non-porous silicon [23].

150   Once the devices filled with adequate adsorbent material, the fluidic connections are made with metallic

151   capillaries (steel) having 220µm of internal diameter The capillary is filed, partially introduced in the device

152   and then fixed with a ceramic cement in order to not block the connectors during the sealing.

153   **2.4. Heating element**

154   In order to have an autonomous component, for either the thermal treatments of the adsorbent materials

155   and the desorption of the trapped gases, a platinum heater is integrated on the backside of the device by

156 screen printing and the electrical connections are made with gold wires pasted on a platinum lacquer. This

157 heating element is used to heat the device at temperatures up to 500°C with a very homogeneous

158 distribution of the temperature considering the good thermal conductivity of the silicon, as it was reported in

159 our previous works [23, 24]. To have a good regulation of temperature, the micro-preconcentrator is suspended

160 in a metallic box (Figure 2).

161

162 **2.5. Optimization of the experimental parameters**

163 Five main parameters are of importance for the optimum operation of a preconcentrator device with a

164 given geometry and filled with a fixed quantity of specific absorbent material: the gas flow rate during the gas

165 adsorption, the gas flow rate during the desorption phases, the heating rate during the gas desorption phase,

166 the duration of the gas adsorption and desorption phases, and the gas volume of the detector.

167 The miniaturization of such device imposes us a limitation on the gas flow rate, but for preconcentration,

168 high flow rates are preferred during the adsorption in order to increase the desorption peak amplitude for a

169 given time of adsorption. The adsorption phase flow was set at 167mL/min, which allowed us to inject a

170 significant quantity of pollutant in a short time, while the desorption phase flow was maintained at 33mL/min

171 to avoid an important dilution of the desorbed quantity. Likewise, to avoid a considerable detection volume,

172 the metallic capillary at the outlet of our micro-preconcentrator was directly connected to the inside of the

173 detector through its packaging (Sensor from FIGARO ref. 2620), and the latter was then calibrated in order

174 to correct the influence of the gas flow on the characteristics of its response [23]. Otherwise, some

175 experiments were initially made with a miniaturized sub ppm PID (Photo Ionization Detector, RAE ppb).

176 Since the maximum of the desorption peak is an increasing function of the heating rate [23], the

177 preconcentration tests were performed with a heating rate of 160°C/min, which corresponds to the maximum

178 rate that can reach the heating resistance deposited on the backside of the micro-channels. the maximal

179 temperature is 350°C.

180 Finally, the increase of the adsorption time can lead to an enhancement of the desorption peak

181 amplitude, but in the same time causes a longer preconcentration cycle which for some applications might

182 not be desirable. Therefore, the adsorption and desorption times were maintained constant all through the

7

183 experiments and lasted for 5 minutes since for these targeted applications as the pollution monitoring, a

184 short preconcentration cycle is more appropriate.

185 So, it is very difficult to define a preconcentration factor since, for a given preconcentrator, the

186 "amplification" of the concentration is closely related to the duration of the gas adsorption phase, the

187 flowrates during adsorption and desorption phases, and the heating rate. However, we will measure a

188 "practical" preconcentration factor which we defined as the ratio between the maximum of the measured

189 concentration during the desorption phase and the concentration of the injected gas.

190 ## 3. RESULTS AND DISCUSSIONS

191 ### 3.1. Specific area measurement

192 The first tests were especially dedicated to the measurement of the specific area of the selected

193 adsorbent materials namely carbon nanopowder, carbon nanotubes (SWCNTs, MWCNTs) and a polymer

194 (Tenax TA) by nitrogen adsorption using the BET method. These results show that the specific area of the

195 activated carbon nanopowder and the SWCNTs nanotubes are higher than the one of the three other

196 adsorbents (Table 1).

197 However, a large specific surface does not mean necessarily a large adsorption capacity because the

198 latter is closely related to the degree of affinity between the adsorbent and adsorbed gas. So the best

199 solution is to evaluate the adsorption capacity of these adsorbents towards to benzene and nitrobenzene.

200

201 ### 3.2. Benzene adsorption

202 *3.2.1. Thermal Programmed Desorption (TPD)*

203 The second series of experiments concerned the evaluation of the adsorption capacity of the adsorbents by

204 TPD technique coupled with a mass spectrometer.

205 The adsorption capacity for benzene of the four adsorbents has been evaluated in similar conditions and

206 in the presence of humidity obtained by bubbling the gas in a bottle of water at ambient temperature. On the

207 one hand, there is a significant desorption peak of water with the activated carbon nanopowder unlike the

208   three other adsorbents which have a low affinity with water vapor (Figure 3). This result reflects a higher

209   decrease of the adsorption capacity of the activated carbon nanopowder in a presence of water, which is

210   very harmful for the experimentation in ambient air. On the other hand, the benzene desorption peak

211   obtained with the activated carbon nanopowder and SWCNTs is about 5 times higher than the one obtained

212   with MWCNTs and Tenax TA. This demonstrates a strong affinity of these two compounds with benzene

213   since the same adsorbent mass has been used for these TPD experiments (Figure 4, 5 and 6).

214   However, it should be noted that the temperature of the maximum of the desorption peak amplitude

215   varies with the adsorbent material. It is estimated at about 120, 180, 280 and 490°C respectively for Tenax

216   TA, activated carbon nanopowder, SWCNTs and MWCNTs, respectively. The high desorption temperatures

217   of the MWCNTs manifest an important activation energy of the desorption synonym with a strong link

218   between the adsorbent and adsorbed gas which is bad for the reduction of the power budget and also for the

219   reliability of the device. Therefore, we decided to not use MWCNTs for the following experiments. It should

220   be noted too secondary benzene peaks between 400 and 600°C, probably due to other sites and

221   mechanisms of adsorption-desorption.

222

223

224   TPD experiments performed with carbon nanopowder deposited on porous and nonporous silicon have

225   shown that the benzene kinetics of desorption on carbon is closely linked to the substrate nature on which

226   the carbon is deposited. Indeed, the desorption temperature of benzene adsorbed on carbon deposited on

227   porous silicon substrate (200°C) is about 60°C lower than the one obtained with a non-porous silicon

228   substrate (260°C) (Figure 7).

229

230   ***3.2.2. Experiments with the micro-preconcentrator***

231   Following the conclusions drawn from the previous TPD experiments presented in the sections above,

232   the preconcentration tests have been performed on silicon and porous silicon micro-channels with a "zigzag"

233   design. In order to study in similar conditions the effect of optimized parameters, the quantity of deposited

234   adsorbent on all micro-channels will be equal to about 1mg.

235   On one hand, the tests of these porous silicon micro-channels with carbon deposition have shown that

236   the porous silicon, besides increasing the quantity of deposited carbon, contributes to the effectiveness of

237   the gas preconcentration by making the desorption easier and thereby reducing the desorption temperature

238   and at last the duration of the preconcentration cycle (Figure 8).

239   This complete desorption of the couple porous silicon-carbon is, maybe, due to its activation energy of

240   desorption lower than the one for the pair non-porous silicon-carbon. The maximum of concentration

241   obtained during desorption is about 15 ppm corresponding to a "practical" factor of preconcentration (as

242   defined above) of about 60.

243

244   On other hand, the preconcentration tests of the non porous silicon micro-channels filled with SWCNTs

245   have shown that the influence of water vapor in the performance of the micro-preconcentrator is lower than

246   the one filled with activated carbon nanopowder, for which the sensor response during the desorption is

247   intensely reduced in presence humidity (Figure 9, 10).

248

249   However, it should be noted that the desorption parameters of the non porous silicon micro-channels

250   filled with SWCNTs are not optimum since we have observed a low factor of preconcentration and a spread

251   of its desorption peak, which is synonym of a insufficient both heating rate (160°C/min) and desorption

252   temperature (240°C). Some experiments are underway to optimize the preconcentration characteristics of

253   the device when using SWCNTs.

254   The other experiments under benzene with SWCNTs and Tenax TA are summarized in the table 2 have

255   shown firstly, the interest of using SWCNTs for reducing of the influence of water vapor during the adsorption

256   phase and secondly, the low desorption temperature when Tenax is used as adsorbent material in

257   opposition of the activated carbon.

258   Others VOCs with high saturation vapor pressure such as xylene have been tested with our micro-

259   preconcentrator and the results are shown in the table 2. They confirm the interest of using Tenax for these

260   typical VOCs.

10

3.3. Nitrobenzene adsorption

3.3.1 Thermal Programmed Desorption

These TPD experiments with nitrobenzene adsorption have shown a strong link between the nitrobenzene molecules and carbon nanopowder particles making thereby the desorption more difficult. Indeed, there is a low desorption of nitrobenzene at 200°C and a high desorption of benzene is observed meaning thus the decomposition of nitrobenzene molecules in benzene at above 300°C (Figure 11). Unlike carbon, the polymer Tenax TA released easily nitrobenzene molecules during the desorption at a temperature below 150°C and no decomposition of the latter is observed since the benzene desorption peak is very small compared to nitrobenzene peak (Figure 12).

3.3.2. Experiments with the micro-preconcentrator

Tests under nitrobenzene realized with a micro-preconcentrator have confirmed that the nitrobenzene molecules are strongly adsorbed on the carbon adsorbent making thus the desorption quasi impossible. As shown in the Figure 13, after a cleaning step at 200°C followed by an injection of 1ppm of nitrobenzene during 120min, no nitrobenzene is desorbed even with a temperature of about 200°C.

In addition, when this experiment has been performed again by heating the micro-preconcentrator until 350°C during one hour, only a small amount of nitrobenzene is desorbed. While the Tenax, after a cleaning step at 150°C followed by an injection of 1ppm of nitrobenzene, a total desorption of the target gas is observed only at 120°C before the end of the heating confirming therefore the TPD observations (Figure 14).

3.4. Summary and perspectives

All these tests experimented with our micro-preconcentrator have shown that the efficiency of the latter is closely related not only to the adsorbent material but also to the nature of the micro-preconcentrator substrate on which the test has been done. Therefore, the table 2 summarizes the results obtained with our

286   micro-preconcentrator with respect to the adsorbent, the nature of the substrate and the target gas. The

287   preconcentration of nitrobenzene with macroprous silicon microchannel filled with carbon adsorbent

288   (symbolized by the question mark) has not been done yet. It will be an interesting test in order to confirm the

289   reduction of the desorption temperature of the nitrobenzene easing thus the use of carbon material for the

290   preconcentration of nitroaromatic gases deriving from explosive compounds.

291

292

293   Another idea now is to reduce the dimension of the microchannel because at the beginning of this project,

294   we opted for a large deposit of adsorbent in the micro-device but over time we realized that for the detection of

295   trace VOCs (concentrations of hundreds of ppb), few milligrams of carbon are efficient to perform these

296   experiences. Therefore, reducing the size of micro-component seems necessary, firstly, to obtain a more

297   compact deposit of the adsorbent promoting interstitial porosity, more uniform distribution of the flow and

298   secondly, to improve the thermal inertia because of its small size (Figure 15).

299

4. CONCLUSIONS

301   The effect of gas preconcentration in micro-channels has been demonstrated following a preliminary

302   optimization of both the microchannel designs and the operating parameters. The use of four different

303   adsorbent materials has been evaluated in a presence or not of relative humidity. To this end, SWCNT

304   appears as adequate adsorbent for preconcentration of benzene in presence of humidity because of its high

305   specific area and adsorption capacity and its low affinity with water vapor. While Tenax TA polymer seems

306   the ideal candidate for the preconcentration of nitrobenzene since the latter is completely desorbed below

307   150°C.

308   Another important result of this study is the development of micro-preconcentrator on porous silicon. In

309   fact, the porous aspect of the micro-preconcentrator substrate contributes to increasing the quantity of

310   adsorbent filled by fluid through the micro-device. Besides this, it facilitates the desorption of gas molecules

311   adsorbed on the adsorbent deposited on it by reducing the temperature of desorption of adsorbent-

312   adsorbate couple. This advantage can also make easy the detection of VOCs with very low vapor pressure

313   of saturation that are very difficult to be desorbed.

314   In addition, the adsorption capacity of the microporous silicon itself is not uninteresting since, due to its

315   low desorption temperature, it could probably be directly used as adsorbent material for certain vapors such

316   as nitrobenzene.

317   Moreover, we are currently studying the preconcentration of VOCs mixture by exploiting the difference of

318   desorption between gases in order to separate their desorption peaks. In this case, the combining of porous

319   silicon and other alternative materials seems an interesting way to improve the performance of our micro-

320   preconcentrator.

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FIGURES

Figure 1: Velocity cartographies obtained after a CFD simulation with microchannels in neural design without channel system at the inlet/outlet for a flow rate of 20L/h (a) and 40L/h (b) and in neutral (c) and zigzag (d) designs with channel system at the inlet/outlet for a flow rate of 20L/h.

Figure 2: Micro-channel in porous silicon filled with carbon with metallic gas capillaries and suspended in metallic box.

Figure 3: TPD spectrum of Carbon nanopowder after benzene adsorption.

Figure 4: TPD spectrum of Tenax polymer after benzene adsorption.

Figure 5: TPD spectrum of SWCNTS after benzene adsorption.

Figure 6: TPD spectrum of MWCNTs after benzene adsorption.

Figure 7: TPD spectrum of carbon nanopowder deposited on porous and non-porous silicon after benzene adsorption.

Figure 8: Comparison of gas sensor response between porous silicon and non porous silicon micro-channels filled with carbon nanopowder after an adsorption step of 250ppb and desorption step at 200°C with a heating rate of 160°C/min.

Figure 9: Sensor response for a silicon micro-channel filled with activated carbon nanopowder with and without humidity, when exposed to 5min to 250ppb of benzene and desorbed during 5min at a temperature of 200°C.

Figure 10: PID response of silicon micro-channel filled with SWCNTs with and without humidity when exposed to 5min to 250ppb of benzene and desorbed at 240°C.

Figure 11: TPD spectrum of Carbon nanopowder after nitrobenzene adsorption

Figure 12: TPD spectrum of Carbon Tenax polymer after nitrobenzene adsorption.

Figure 13: PID response of a silicon micro-channel filled with activated carbon nanopowder when exposed to 120min to 1ppm of nitrobenzene and desorbed at a temperature of 200°C.

Figure 14: PID response of a silicon micro-channel filled with Tenax TA when exposed to 45min to 1ppm of nitrobenzene and desorbed a temperature of 140°C.

Figure 15: Pressure and velocity cartographies obtained after a CFD simulation at 20 L/h with a new microchannel in neutral design.

TABLES

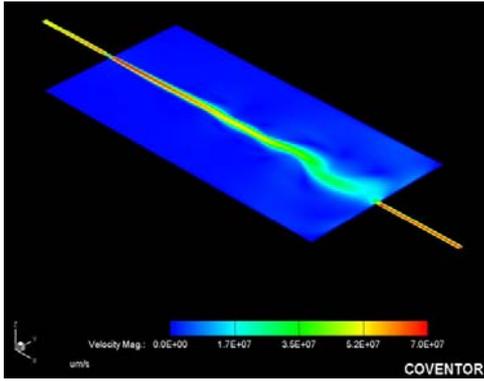Table 1: Specific area and particle size of different adsorbents.

Table 2: Summary of results obtained with our micro gas preconcentrator according the adsorbent material, the preconcentrator substrate and the target gas. Symbols +++, ++, + and – mean respectively very good, good, medium and bad results

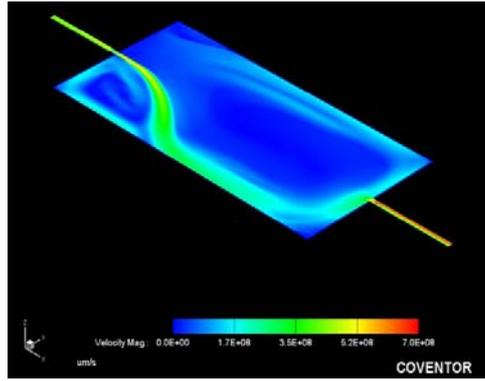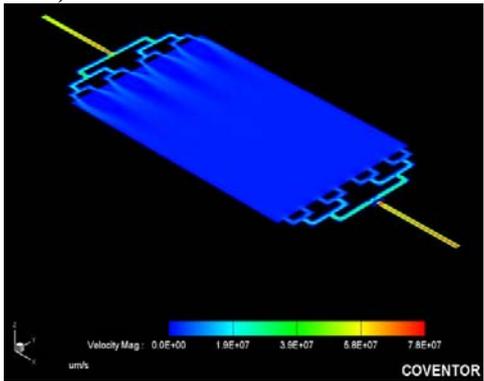| Adsorbent	Specific area (m^2/g)		Particle size (µm)
Carbon nanopowder	99	+/-1	0.1
Activated carbon nanopowder	490	+/- 8	0.1
SWCNTs	399	+/- 5	2
MWCNTs	21	+/- 1	5
Tenax TA	35	+/- 2	250

Table 1: Specific area and particle size of different adsorbents.

Gas Adsorbent/Substrate	Benzene	Xylene	Nitrobenzene
Carbon / Silicon	+ + +	+ +	−
Carbon / Macroporous silicon	+ + +	+ ++	**NA**
SWCNTs / Silicon	+ +	+	−
SWCNTs /Macroporous silicon	+ + +	+ + +	
Tenax TA / Silicon	+ +	+ +	+ +

Table 2: Summary of results obtained with our micro gas preconcentrator according the adsorbent material, the preconcentrator substrate and the target gas, +++, ++, + and – mean respectively very good, good, medium and bad results, .
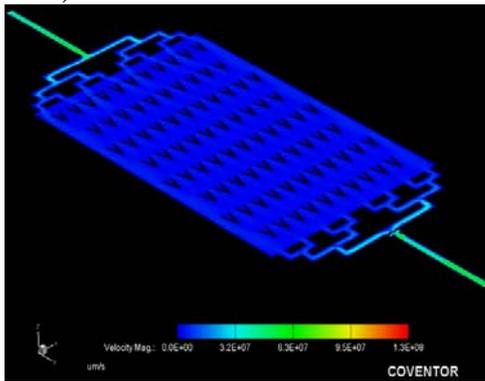
a)

b)

c)

d)