Research Article

Matej Sedlar, Majda Pavlin, Arkadij Popovič, Milena Horvat*

Temperature stability of mercury compounds in solid substrates

Abstract: The major aim of the newly adopted Mercury Convention is to reduce global mercury (Hg) emissions to the environment. In high temperature industrial processes, including coal combustion, Hg compounds present as impurities in solid materials are decomposed and evaporated leading to the emission of Hg to the atmosphere. The behaviour of different Hg compounds and their mixtures during heating have been the subject of numerous studies, and is the topic of the present work. Controlled heating can be used to fractionate Hg compounds in solid substrates, offering the possibility of identification and quantification of Hg compounds. In the attempt to develop a method for temperature fractionation of Hg, experiments were conducted with pure Hg compounds, and the compounds mixed with different substrates (SiO₂ and CaSO₄ • 2H₂O), for calibration purposes. Detection was performed by two methods, namely Cold Vapour Atomic Absorption Spectrometry (CV AAS) with Zeeman background correction, and Nier-type Mass Spectrometry with a Knudsen cell (MS). Further investigation is in process.

Keywords: mercury compounds, temperature fractionation, substrate, CV AAS, mass spectrometry.

1 Introduction

Hg, as a global pollutant, originates from natural and anthropogenic sources, mainly by unintentional release into the environment. Industrial processes, such as burning of fossil fuels, the cement industry, oil refining, gold mining and others represent the biggest anthropogenic Hg sources, emitting more than 2000 tons per year, which represents around 30% of the total amount of Hg entering the atmosphere each year [1]. Due to the global nature of Hg pollution a new legally binding convention was adopted in 2013 with the main aim of reducing anthropogenic Hg emissions [2].

Hg in the environment exists in different forms such as elemental Hg(0), oxidized Hg(I) and Hg(II), or Hg associated with particulate matter, Hg(p) [3]. In the environment the formation of monomethylmercury (MeHg) is of concern because of its toxicity and bioaccumulation and biomagnification in aquatic and terrestrial food webs. Transformations between these forms are the basis of complex biogeochemical cycling of local and global relevance [2]. In solid matrices and industrial samples, Hg can be found as e.g. HgS (cinnabar, metacinnabar), HgCl₂, HgO, HgSO₄, with different degrees of solubility and temperature stability [4-8].

The method of temperature fractionation could be used to verify the decomposition temperatures of different Hg compounds and to identify Hg species in solid samples. Decomposition/sublimation temperatures of some Hg compounds are shown in Table 1.

Some methods involving different approaches have been tested by Biester and Scholz [4], Shuvaeva et al. [12], Lopez-Anton et al. [13], Rallo et al. [14], Luo et al. [15], Bollen et al. [16], Iwashita et al. [17], Wu et al. [18], Coufalik et al. [19,20] etc. However, no procedure for temperature fractionation of Hg has been validated or standardized yet, and therefore its comparability is questionable due to procedural differences. Validation of the method is necessary for further comparison of results and identification of Hg compounds.

Hence the aim of this work was to investigate the performance of the pyrolysis method based on CV
AAS detection, which is frequently used in various laboratories [4,8-20]. A comparative method based on mass spectrometry was used to better understand the temperature stability and reaction mechanisms of different Hg compounds in solid materials. The long-term goal of this work was to develop a methodology for the identification of Hg compounds in environmental and industrial solid materials and their transformation on heating.

## 2 Methods

### 2.1 Preparation of Hg compounds with substrates

Nine different Hg compounds (Table 2) were selected for examination (HgS, HgSe, HgO (red and yellow), HgSO₄, Hg₂SO₄, HgF₂, HgCl₂, and Hg₂Cl₂).

These compounds were “diluted” by mixing the pure compound with two different substrates: SiO₂ or CaSO₄ • 2H₂O powders. The first is frequently used for “diluting” pure Hg compounds for calibration purposes, while the second resembles gypsum from the wet desulfurization in coal burning power plants. Each pure Hg compound (1-4 mg when mixing with SiO₂, and 10-12 mg when mixing with CaSO₄ • 2H₂O) was added to 5 g of substrate powder. The mixtures were carefully homogenized by mixing in a zirconium container that was placed in a planetary mill (Fritsch planetary mill Pulverisette 7). The bulk homogeneity of the prepared mixtures was checked by six independent analyses of total Hg. A sample of weight between 80-140 mg was acid digested and Hg was determined by CV AAS after the reduction with SnCl₂ [21].

### 2.2 Experimental Apparatus for Temperature Fractionation

#### 2.2.1 Apparatus 1

An RA-915+ Mercury Analyser with a PYRO-915+ pyrolysis unit was used for the detection of Hg. The instrument was developed for direct determination of the total Hg by combustion of samples and cold vapour atomic absorption detection (CV AAS) with Zeeman background correction [22].

The apparatus used for temperature fractionation was a home-constructed device, presented in Fig. 1. It consisted of a gas tank (1) for the supply of carrier gas, a flow meter (2) for flow adjustment and quartz tubes. The first quartz tube was placed in the electric tube furnace (3). The quartz boat used for samples (4) was carefully positioned in the first quartz tube in the middle of the electric tube furnace. The second quartz tube was packed with quartz wool (5).

### Table 1. Accessible literature data about the temperature characteristics of mercury compounds.

<table>
<thead>
<tr>
<th>Mercury compound</th>
<th>Temperature of decomposition or sublimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury(I) chloride</td>
<td>HgCl₂</td>
</tr>
<tr>
<td>Mercury(II) chloride</td>
<td>HgCl₂</td>
</tr>
<tr>
<td>Mercury(I) oxide</td>
<td>HgO</td>
</tr>
<tr>
<td>Mercury(II) oxide</td>
<td>HgO</td>
</tr>
<tr>
<td>Mercury(II) sulfide – (Red)</td>
<td>HgS</td>
</tr>
<tr>
<td>Mercury(II) selenide</td>
<td>HgSe</td>
</tr>
<tr>
<td>Mercury(II) sulfate</td>
<td>Hg₂SO₄</td>
</tr>
<tr>
<td>Mercury(I) sulfide</td>
<td>HgSO₄</td>
</tr>
<tr>
<td>Mercury(I) fluoride</td>
<td>HgF₂</td>
</tr>
<tr>
<td>Mercury(II) fluoride</td>
<td>HgF₂</td>
</tr>
</tbody>
</table>

### Table 2. Type of mercury compound, suppliers and purity.

<table>
<thead>
<tr>
<th>Mercury compound</th>
<th>Supplier</th>
<th>Declared purity of mercury compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>HgCl₂</td>
<td>Sigma-Aldrich Co. LLC.</td>
<td>≥ 99.5%</td>
</tr>
<tr>
<td>HgCl₂</td>
<td>Kemika d.d., Zagreb</td>
<td>99%</td>
</tr>
<tr>
<td>HgO – Red</td>
<td>Sigma-Aldrich Co. LLC.</td>
<td>≥ 99.5%</td>
</tr>
<tr>
<td>HgO – Yellow</td>
<td>May &amp; Baker Ltd.</td>
<td>≥ 99.5%</td>
</tr>
<tr>
<td>HgS – Red</td>
<td>Mallinckrodt Chemical Works</td>
<td>99%</td>
</tr>
<tr>
<td>HgSe</td>
<td>Sigma-Aldrich Co. LLC.</td>
<td>99.9%</td>
</tr>
<tr>
<td>Hg₂SO₄</td>
<td>Sigma-Aldrich Co. LLC.</td>
<td>98%</td>
</tr>
<tr>
<td>HgSO₄</td>
<td>Sigma-Aldrich Co. LLC.</td>
<td>≥ 99%</td>
</tr>
<tr>
<td>HgF₂</td>
<td>Sigma-Aldrich Co. LLC.</td>
<td>97%</td>
</tr>
</tbody>
</table>
and heated to 800°C by a small electric furnace (6) to ensure the transformation of all volatile Hg compounds to elemental Hg and to retain any particles that might be released from the sample. The Lumex Pyro 915+ pyrolysis unit (7) ensured additional decomposition of any remaining volatile compounds of Hg that might interfere with the atomic absorption measurement [22]. Elemental Hg was detected by the Lumex Ra-915+ atomic absorption detector with Zeeman correction (8), which was connected directly to a computer (9) for data collection. An impinger containing $\text{H}_2\text{SO}_4$–$\text{KMnO}_4$ solution (10) was connected to the exhaust from the Lumex Ra-915+ to retain Hg(0) in solution by oxidation.

2.2.2 Procedure 1

Testing was conducted with pure Hg compounds and those mixed with $\text{SiO}_2$ or $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. An amount of up to 0.2 mg of the sample was directly weighed into a quartz boat and tested without any pre-treatment for the pure Hg compounds. The Hg compounds homogeneously mixed with $\text{SiO}_2$ or $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, and the sample weight varied from 9 to 30 mg. The sample boat (4) (Fig. 1) was carefully positioned in the middle of the quartz tube which was heated at room temperature of up to 750°C with a linear heating rate of approximately 2.2°C min$^{-1}$. Nitrogen or air was used to flush Hg vapour released from the sample through the measurement train at a flow rate of 1 L min$^{-1}$.

2.3 Mass spectrometry

2.3.1 Apparatus

As a measuring device, a Nier – type mass spectrometer was used, initially designed for Knudsen Effusion Mass Spectrometric measurements, known as the KEMS method. The current sample was not loaded into the Knudsen cell; instead it was loaded into a semi-closed quartz inlet tube 10 cm long with 3 mm inner diameter, with the opened end tightly inserted into the circular hole drilled in a block of the ionization chamber of the Nier ion source. Such an arrangement provided for all desorbed species to be entered into the ionization volume and significantly improving the sensitivity compared with standard KEMS.

The typical amount of mercury necessary to obtain a reliable thermodynamic spectrum is 100 ng contained in up to a 5 mg sample. The closed end of the inlet tube with a sample, positioned outside the spectrometer, was heated resistively with the temperature ramp of 10°C min$^{-1}$, using a EUROTHERM regulator. Ni/CrNi thermocouple was used for the temperature measurement. The desorbed atomic and/or molecular species were ionized by an electron of...
35 eV energy and a 10 µA trap current. Ions were extracted from the ionization space through an extraction slit, accelerated with –2 kV and analysed by a 60 degree magnetic separator according to their m/z ratio. Ions were finally detected by the ETP electron multiplier operating in counting mode and registered on counts per second base using an acquisition computer, together with temperature information.

It should be noted that desorption in MS experiments takes place at high vacuum conditions (better than 10⁻⁴ Pa). Species once desorbed are instantly detected by the detection system, within milliseconds. Thus, any change in the desorption process is instantly observed. The interaction between desorbed species and inner walls is low, compared with the transpiration method (CV AAS). It should be mentioned, that the rather turbulent flow of the carrier gas might blur the possible fine structure of thermodynamic curves due to the mixing effects.

In principle, the use of a mass spectrometer enabled us to detect any molecular species involved during the desorption process. However, in this work we were preferably interested in the shapes of thermodynamic curves to answer whether or not their shapes could be used for mercury speciation. For this reason, we were mainly concerned regarding the mercury that contained ions and/or their precursors. Since HgO, HgS, HgSe, Hg₂SO₄, and HgSO₄ are thermally unstable compounds, only atomic Hg could be expected as the desorption species. On the contrary, HgCl₂ and HgF₂ are according to the literature data stable upon heating, and ions such as HgCl₂⁺, HgCl⁺, HgF₂⁺ and HgF⁺ might be found in mass spectra.

2.3.2 Procedure

Only Hg compounds mixed with SiO₂ and CaSO₄ • 2H₂O were used. In this procedure the heating of the samples was conducted at a heating rate of 10°C min⁻¹ from room temperature to 550°C in a low pressure atmosphere. The reason for the heating to only 550°C was due to the material of the measuring line having a higher melting temperature.

In the series of measurement in which SiO₂ was used as a substrate for Hg compounds, the measurement method was adjusted by enlargement of the effusion orifice and the reduction of the amount of sample due to its binding to the surface of the substrate. This caused a reduction in the sample so that the intensity of the signal could not cope with the exponential function of the temperature. This resulted in a desorption peak. Despite the fact that in such conditions the saturation vapour pressure was not reached, the possibility of a re-adsorption of Hg species still existed before they left the Knudsen cell. A second series of measurements on Hg compounds where CaSO₄ • 2H₂O was used as the substrate. Samples were inserted directly into the ionization area of the spectrometer through a quartz tube. This method differed from the first one by ensuring the introduction of every single desorbed molecule to the ion source, causing a significant amplification of the detection sensitivity. Additionally, the larger orifice reduced the possibility of re-adsorption. This made a substantial impact on the structure of the dynamic thermal curves. With this method, the pressure inside the insertion tube was much lower than the saturation pressure due to the faster outflow of gas, as compared to the velocity of the desorption process.

3 Results

3.1 Temperature fractionation results

The results are shown as graphs (thermograms) of temperature versus the relative intensity of Hg peaks to allow a comparison of the thermograms from different compounds. Thermograms are described for each Hg compound separately below.

The results for each Hg compound are presented in three figures. The first two present results obtained with CV AAS and the third with MS. Three sets of experiments were conducted using CV AAS; the pure Hg compound was followed by the Hg compound mixed with SiO₂ or with CaSO₄ • 2H₂O. The three thermograms obtained by CV AAS are presented in two separate figures for each Hg compound. The first was obtained in a flow of nitrogen and the second in a flow of air. Results were obtained as an average of at least two replicates. The third figure in each set of experiments represents the results obtained by MS.

In general, the comparison of the thermograms obtained by CV AAS and MS shows that the temperatures at which Hg peaks appear differ. In most cases the peak maxima appear at higher temperatures for the CV AAS method compared to MS due to different conditions regarding a low pressure atmosphere of the MS method procedure. The comparison of the results obtained by CV AAS indicated that the parameters of the experimental set-up, such as carrier gas, heating rate, flow rate and substrate may have played an important role in Hg release during heating, and therefore constant conditions had to be maintained during repetitive experiments.
3.1.1 Hg$_2$Cl$_2$:

The thermograms obtained by CV AAS are shown in Figs. 2 and 3. The shape of the thermogram of pure Hg$_2$Cl$_2$ was smooth and ranged between 50 to 300°C with a major peak of 75°C and 78°C for nitrogen and air as carrier gases, respectively. The pure compound mixed with SiO$_2$ resulted in wider peaks at 165°C and 146°C for nitrogen and air, respectively. It is assumed that the larger surface area provided by the substrate affected the release of Hg during heating. Three main peaks could be seen for CaSO$_4$ • 2H$_2$O as a substrate. The first peak ranged between 50 to 140°C with peak maxima of 93°C and 87°C for nitrogen or air as carrier gases, respectively. The shape and the temperature were similar to the peaks obtained for pure Hg$_2$Cl$_2$. The second peak was much broader compared to the other peaks and ranged from 140 to 500°C with peak maxima of 273°C and 223°C when purged with nitrogen or air, respectively. It was assumed that two or more peaks were hidden by the wide peak. The third sharp peak appeared at a much higher temperature, with peak maxima of 680°C and 623°C for nitrogen and air respectively.

The appearance of the second and third peaks was clearly attributed to the presence of CaSO$_4$ • 2H$_2$O which decomposed and probably reacted with Hg.

During heating, Hg$_2$Cl$_2$ disproportionate to Hg(0) and HgCl$_2$ (Eq. 1) decomposed to elemental Hg and Cl$_2$ (Eq. 2) [13].

\[
\text{Hg}_2\text{Cl}_2 \leftrightarrow \text{Hg}^0 + \text{HgCl}_2 \quad (1)
\]

\[
\text{HgCl}_2 \leftrightarrow \text{Hg}^0 + \text{Cl}_2 \quad (2)
\]

The vapour pressures of the gaseous products HgCl$_2$ and Hg were the same (130 Pa at 136°C), and for that reason both gaseous products were released at the same temperature [18] resulting in one main peak (Figs. 2 and 3). Interestingly, in recent work Lopez-Anton et. al., reported two major peaks for Hg$_2$Cl$_2$ mixed with SiO$_2$ [13]. In our case, another small peak was also visible at lower temperatures (at 90°C when purged with nitrogen) when SiO$_2$ was used as the substrate. This could be explained by a possible decomposition of Hg$_2$Cl$_2$ to Hg(0) and HgCl$_2$, which could have been caused by exposure to the light [10].

The appearance of the third peak at temperatures above 600°C is difficult to explain as no theoretical background exists. The sharp shape of this peak suggests that the appearance of this peak might be due to an experimental artefact induced by breakdown processes during heating and the subsequent formation of less volatile Hg compounds that could be adsorbed on cooler surfaces of the experimental set-up. On increasing the temperature of the carrier gas, these compounds were probably released when the critical temperature was reached. However, the possibility also exists that during the decomposition steps a complex compound was formed.

The results obtained by mass spectrometry are shown in Fig. 4. As mentioned in the experimental part, pure compounds without substrates were not used in the MS experiments. The appearance of the main peaks at temperatures of 84°C and at 110°C was observed for HgCl$_2$ with SiO$_2$ and CaSO$_4$ • 2H$_2$O as substrates. On the thermogram of Hg$_2$Cl$_2$ mixed with CaSO$_4$ • 2H$_2$O, a small peak can be seen at the lower temperature of around 80°C. This peak was probably caused by the release of Hg(0) adsorbed on the powder as a result of the decomposition of Hg$_2$Cl$_2$ due to exposure to light [10]. Although the thermograms obtained by the CV AAS set-up and MS
seemed different, particularly for Hg\(_2\)Cl\(_2\) mixed with CaSO\(_4\) • 2H\(_2\)O, the peak pattern initially followed the same trend with a skew towards higher temperatures. The reason for that can probably be found in the procedure of the MS method which operates in a near vacuum. Therefore the sample almost instantaneously entered the measuring cell after the decomposition of the sample, unlike the CV AAS method where Hg needed to be purged into the measuring cell. Unfortunately the MS system could not be used at a temperature above 400°C to verify whether the appearance of Hg peak above 600°C using CV AAS was associated with an experimental artefact.

3.1.2 HgCl\(_2\):

The results for HgCl\(_2\), measured by CV AAS were similar to those for Hg\(_2\)Cl\(_2\) (Figs. 4 and 5), although with less smooth peak shapes. The major peak of the pure compound appeared at slightly higher temperatures and completely covered the first peak of the Hg compound mixed with CaSO\(_4\) • 2H\(_2\)O. The second and third peaks of HgCl\(_2\) mixed with CaSO\(_4\) • 2H\(_2\)O appeared in the same temperature range as the second and third peaks of Hg\(_2\)Cl\(_2\) mixed with CaSO\(_4\) • 2H\(_2\)O.

The literature data suggests that HgCl\(_2\) sublimes, but it can also be stabilized by the supporting material due to the adsorption; or it decomposes to elemental Hg when it comes in contact with the surface of the matrix [18]. Other authors also reported one peak only when heating mixed with SiO\(_2\) [4]. It is obvious that the heating rate and flow rate influence Hg release from the substrates [4,13]. Since gaseous HgCl\(_2\) and Hg [18] have the same vapour pressure, only one peak could be seen for the pure Hg compounds. When HgCl\(_2\) was mixed with substrates, the first small peak probably belonged to the elemental Hg as a result of the preliminary decomposition of the compound. It is assumed, that the presence of the substrate could shift the temperature of the decomposition to higher values, as seen in Fig. 5. The presence of a third peak at temperatures of more than 500°C for HgCl\(_2\) mixed with CaSO\(_4\) • 2H\(_2\)O could be explained by the artefact phenomenon, or formation of a complex compound, as already mentioned for Hg\(_2\)Cl\(_2\).

The MS thermograms (Fig. 7) were also similar to those of Hg\(_2\)Cl\(_2\). The mass spectrum of HgCl\(_2\) is known. Upon ionization of the HgCl\(_2\) molecule, 60% of HgCl\(_2^+\), 4% of Hg\(^+\) and 36% of Hg\(^+\) ions were created [23]. Therefore if Hg was desorbed in the form of HgCl\(_2\), more HgCl\(_2^+\) than Hg\(^+\) ion should have been found in the mass spectrum. This was not the case, however. The great majority (100/1)
of ions in the desorption spectra were observed to be Hg⁺, indicating mostly a dissociative desorption process.

The maximal peak temperature, shown on the thermogram (Fig. 7) was at 92°C whereby SiO₂ was used as the substrate and 130°C for CaSO₄·2H₂O. As observed from the results of the MS method (Fig 7), both first peaks probably belonged to elemental Hg due to the decomposition of HgCl₂ during the mechanical treatment or exposure to sunlight, while the second could be related to the interactions or reactions with the substrate.

### 3.1.3 HgO:

Red and yellow HgO were investigated. Both have the same orthorhombic crystalline structure, but differ in particle size, with the yellow HgO having a smaller particle size [24]. The thermograms obtained are presented in Figs. 8-12. Those obtained for red HgO purged with nitrogen and air are shown in Figs. 8 and 9. The thermograms are similar for both gases, with the exception of HgO on SiO₂ where the peak appears at a lower temperature. Hg was released in one main peak and some smaller but irregular peaks. Some recent publications reported that the decomposition of pure HgO occurred at around 400°C for the yellow and 460°C for the red form [24], although the detailed study of L’vov [25] suggested a multi-step decomposition; the lowest at 160-220°C, intermediate at 220-400°C and higher at 400-500°C. L’vov suggested that the primary product of the HgO decomposition was not molecular oxygen as suggested by most papers (Eq. 3), but monoatomic oxygen (Eq. 4) leading to reaction of gaseous Hg with monoatomic oxygen and formation of Hg₂O (Eq. 5). This may explain our results for pure HgO (red curve), where the small peaks at lower temperature correspond to Hg₂O [26] which decomposes at 100°C to HgO and Hg, and the prevailing peak representing the decomposition of HgO (Fig. 8).

\[
\text{HgO}(s) \rightarrow \text{Hg}(g) + \frac{1}{2} \text{O}_2(g) \quad (3)
\]

\[
\text{HgO}(s) \rightarrow \text{Hg}(g) + \text{O}. \quad (4)
\]

\[
\text{Hg}(g) + \text{O}. \rightarrow \text{Hg}_2\text{O} \quad (5)
\]

The most striking peak was that of HgO mixed with SiO₂ at about 265°C (Fig. 8). It seems that the substrate in this case facilitated the decomposition of HgO at a much lower temperature than for the pure HgO. This trend is the opposite to the other Hg compounds such as HgCl₂ (Fig. 5) between thermograms obtained for pure compounds and those mixed with SiO₂. Some recent studies [27,28] suggested that a number of silicate compounds (i.e., HgSiO₃, Hg₆Si₂O₇, etc.) could possibly be formed within cement kiln systems. The decomposition temperature of these compounds was reported to be between 225 and 325°C [29] which would be consistent with our results. In addition, the reaction mechanisms induced by autocatalysis, as suggested by L’vov [25], on the larger surface of SiO₂ may shift the decomposition of HgO through formation of Hg₂O, which is typical of lower temperature range decomposition. As seen on the thermograms (Figs. 8 and 9) the main peak of HgO on SiO₂ corresponded to the lower temperature range decomposition peaks of pure HgO. Further support for this hypothesis was evidenced by a reproducible small peak appearing at a temperature of about 130°C which most probably corresponds to Hg(g) likely resulting in autocatalytic formation of Hg₂O. This mechanism still needs to be better understood.

The mixture of HgO and CaSO₄·2H₂O released its major peak at a similar temperature as pure HgO (Figs. 8 and 9). However the peak shape skewed towards lower temperatures indicated the decomposition and subsequent release of Hg at maximum temperatures between 300 to 350°C. Even the shapes were similar, but a slight shift could be seen towards lower temperatures. The lower peak that appeared was relatively greater, compared to samples of pure HgO.

The thermograms obtained by MS are presented in Fig. 10 for red HgO mixed with SiO₂ or CaSO₄·2H₂O substrates. The first peak appeared ranged between 75 and 125°C and was most probably a result of the release of Hg(0) due to the decomposition of HgO. The temperatures of the second peak differed by around 40°C, where SiO₂...
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caused the earlier release of Hg, shifting it towards a lower temperature (208°C) compared to CaSO$_4$ • 2H$_2$O (247°C). A similar shift was observed at the release of a third peak as well.

HgO (yellow) (Figs. 11 and 12) has similar characteristics to HgO (red) during the temperature decomposition, when followed by the CV AAS method.

It is evident that for pure Hg compounds mixed with CaSO$_4$ • 2H$_2$O, air had a large influence on the release of Hg, probably due to interactions with the substrate. Despite the fact that the release of Hg began at around 100°C, the structural changes caused by air as the carrier gas accelerated the release of Hg. This could be the reason why the peaks of the Hg compound mixed with CaSO$_4$ • 2H$_2$O differed in pattern compared to the thermograms of the same compound in a different carrier gas.

Thermograms of HgO (yellow) obtained by MS are presented in Fig. 13, indicating a similar pattern of Hg release from HgO on both substrates. Three peaks can be seen, of which the main appears at 190-220°C. A slight temperature shift towards lower temperatures was observed with HgO on SiO$_2$ as the substrate. The small peak appearing in the temperature range of 75-125°C probably belongs to Hg(0). As seen in the MS thermograms of both HgO compounds, the pattern of peaks was similar. Multistep decomposition was present and comparison shows that particle size plays an important role in the release of Hg.
If also considering fugacity effects, the reaction rate may be significant at lower temperatures [30]. As the authors claim, HgS decomposes before melting by a process also referred to as reactive sublimation which proceeds according to Eq. 6 [30]. It also seems that the flow rates and substrates have minor effects on the temperature at which the decomposition of HgS is detected.

\[
\text{HgS} \rightarrow \text{Hg} + \frac{1}{2} \text{S}_2 \tag{6}
\]

When O$_2$ was present in the carrier gas, the evolution of SO$_2$ was observed by Wu et al., though the thermogram was almost identical to that in the absence of O$_2$ [18].

\[
\text{HgS} + \text{O}_2 \rightarrow \text{Hg}^0 + \text{SO}_2 \tag{7}
\]
When considering the literature data, the existence of an intermediate HgSO$_3$ is also possible, but true identity of HgS decomposition is still not proven [18].

Thermograms for HgS obtained by MS exhibited one peak only (Fig. 16). When mixed with SiO$_2$, Hg was released at 242°C, but when CaSO$_4$ • 2H$_2$O was used as the substrate, the temperature of release was 251°C.

Similarly to HgS, HgSe shows one peak at about 265°C, regardless of substrate and carrier gas (Figs. 17 and 18). Fig. 19 presents the thermograms of HgSe mixed with SiO$_2$ or CaSO$_4$ • 2H$_2$O, measured by MS. The peaks were released at 200°C when SiO$_2$ was used as the substrate, and at 240°C when CaSO$_4$ • 2H$_2$O was used.

Interestingly, HgSe mixed with CaSO$_4$ • 2H$_2$O showed a small peak appearing at a higher temperature of around 280°C. This smaller peak appeared at almost all conditions (substrate, carrier gas), so the effect of the substrate could not have been the cause.

### 3.1.5 Hg$_2$SO$_4$

The CV AAS thermograms for pure Hg$_2$SO$_4$ (Figs. 20 and 21) showed three peaks, the first at 296°C, the second at 375°C, and the third at 510°C for nitrogen as the carrier gas. The maximum temperatures were similar for air. The three peaks could not be easily explained. According to literature data [11] the decomposition of Hg$_2$SO$_4$ involves three steps. The first stage is disproportion at lower temperatures (Eq. 8) as follows:

$$\text{Hg}_2\text{SO}_4(s) \rightarrow \text{Hg}(g) + \text{HgSO}_4(s)$$ (8)

In the second stage, the decomposition of mercury(II) sulphate results in the formation of the basic sulphate, Schuetteite (HgSO$_4$ • 2HgO), SO$_2$ and O$_2$ (Eq. 9):

$$3\text{HgSO}_4(s) \rightarrow \text{HgSO}_4 \cdot 2\text{HgO}(s) + 2\text{SO}_2(g) + \text{O}_2(g)$$ (9)

In the third stage HgSO$_4$ • 2HgO decomposes producing volatile elemental Hg:

$$\text{HgSO}_4 \cdot 2\text{HgO}(s) \rightarrow 3\text{Hg}(g) + \text{SO}_2(g) + 2\text{O}_2(g)$$ (10)

The first peak on the thermogram could be associated with the first reaction (Eq. 8), but the subsequent peaks are difficult to interpret. According to the reactions above (Eqs. 8, 9, 10), Tariq and Hill reported two peaks for mercury(I) sulphate, where the heating rate showed almost no influence [11]. It is believed that the intermediate peak in our case may have represented the
temperature instability of HgSO₄•2HgO at a much slower heating rate.

The thermograms showed a stepwise Hg release from room temperature up to about 350°C with a maximum at 257°C when purged with nitrogen for HgSO₄ mixed with SiO₂. Regarding the air, a slight shift towards higher temperature was observed. These results are comparable with the thermograms published by Lopez-Anton et al. with their results differing for about 20°C towards higher temperature, although they used a much faster heating rate [13]. The substrate clearly affected the release of Hg by lowering the temperature of the major peak.

Four peaks could be seen (Figs. 20-22) for HgSO₄ mixed with CaSO₄•2H₂O. Three of these peaks were quite consistent with the peaks shown by pure Hg₂SO₄, with a slight downward shift of about 20°C of the peak maximum towards a lower temperature when purged with nitrogen. When purged with air the peak maximum appeared at almost the same temperature as the peak maximum of pure Hg₂SO₄. Besides the major peak, two other peaks could be observed, the first at a temperature of about 260°C and the second at a temperature of 330°C. The small peak which could be seen in the range of 25°C to 100°C regardless of carrier gas used, probably represented unbound Hg(0) that could be released from the Hg compound during the mechanical pre-treatment of the sample.

Four peaks for HgSO₄ mixed with SiO₂ and CaSO₄•2H₂O, with a peak maximum at 218°C, were obtained by MS. Smaller peaks appeared at 275°C and at 390°C in the mixture with SiO₂, while other smaller peaks appeared at higher temperatures (375°C and 435°C) for the CaSO₄•2H₂O substrate. In addition to these listed peaks, HgSO₄ with both substrates also had another peak in common at lower temperatures at about 70-80°C. This also occurred in the thermograms of other Hg compounds, most probably related to Hg(0) formed as a result of the decomposition and subsequent desorption of Hg(0).

The appearance of multiple peaks can be explained as suggested above for the CV AAS method, with the exception of the first peak which may be related to the presence of Hg(0) in the samples itself [11].

3.1.6 HgSO₄:

The thermograms obtained by CV AAS (Figs. 23 and 24), showed large differences in shapes for pure HgSO₄ and those where HgSO₄ was mixed with CaSO₄•2H₂O or SiO₂. Pure HgSO₄ showed one main peak at a temperature of 545°C or 565°C for nitrogen or air, respectively. Similar thermograms were obtained for HgSO₄ mixed with CaSO₄•2H₂O. Small Hg peaks could also be observed in the temperature range between 200 and 470°C. Although one step decomposition was suggested by some authors, it seems more likely that HgSO₄ decomposes through several stages [11,15,20,31] (Eqs. 9 and 10). Collins et al. suggested that mercury (II) sulphate may sublime, as confirmed by the detection of a peak in the mass spectra which corresponds to Hg²⁺ [31].

When HgSO₄ was mixed with SiO₂ and purged with nitrogen, a multistage decomposition occurred in the temperature range from room temperature to 570°C with several irreproducible peaks. When air was used as the carrier gas, three main peaks could be seen in the range from 60 to about 600°C. Multiple and irreproducible peaks may reflect unstable intermediate breakdown
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processes due to slow heating and/or interactions with the substrate.

A multistep decomposition can be seen in the thermogram of HgSO\textsubscript{4} mixed with SiO\textsubscript{2} (Fig. 25), as mentioned by Collins et al. [31], and Tariq and Hill [11], while HgSO\textsubscript{4} mainly showed a single step decomposition when mixed with CaSO\textsubscript{4} • 2H\textsubscript{2}O, although its decomposition through several stages is more likely (Eqs. 9 and 10) [11]. The explanation for a single peak could be found in the first step of the decomposition without the production of a volatile Hg compound (Eq. 9) [11]. The four peaks that appeared during thermal decomposition of the Hg compound mixed with SiO\textsubscript{2} occurred at 90°C, 280°C and 415°C, with the major peak at 175°C. HgSO\textsubscript{4} mixed with CaSO\textsubscript{4} • 2H\textsubscript{2}O displayed a peak at a temperature of 460°C.

In comparison with the CV AAS method, MS revealed a much clearer decomposition when mercury(II) sulphate was mixed with SiO\textsubscript{2}, although the temperature range of Hg release was quite similar (room temperature to 475°C). In comparing the methods for HgSO\textsubscript{4} mixed with CaSO\textsubscript{4} • 2H\textsubscript{2}O, a similar decomposition could be assumed, although the Hg compound tested with CV AAS method showed a larger second peak than when tested by the MS method. As already evident from the thermograms of the CV AAS method, the substrate and carrier gas significantly affected the release of Hg from HgSO\textsubscript{4}.

![Figure 21: Thermograms of Hg\textsubscript{2}SO\textsubscript{4}, purged with air.](image)

![Figure 23: Thermograms of HgSO\textsubscript{4}, purged with nitrogen.](image)

![Figure 22: Thermograms of Hg\textsubscript{2}SO\textsubscript{4} mixtures, obtained by MS.](image)

![Figure 24: Thermograms of HgSO\textsubscript{4}, purged with air.](image)
3.1.7 $\text{HgF}_2$:

According to the literature data, $\text{HgF}_2$ is not a stable compound, and is usually found as $\text{HgF}_2 \cdot 2\text{H}_2\text{O}$ or $\text{HgFOH}$ [32]. Pure $\text{HgF}_2$ could be formed by the disproportionation of $\text{Hg}_2\text{F}_2^+$ when heated above 570°C. $\text{HgF}_2$ then decomposed at 645°C [33].

$$\text{Hg}_2\text{F}_2(s) \rightarrow \text{HgF}_2(s) + \text{Hg}(g) \quad (11)$$

Compared with other halides, $\text{HgF}_2$ has a very high melting and boiling point due to its ionic structure. This property causes the decomposition (dissociation) of $\text{HgF}_2$ when it is in contact with water and a fast transformation into $\text{HgO}$ occurs [33].

$$\text{HgF}_2 + \text{H}_2\text{O} \leftrightarrow \text{HgO} + \text{HF} \quad (12)$$

However, the experiments with CV AAS and MS indicated that pure $\text{HgF}_2$ and $\text{HgF}_2$ mixed with $\text{SiO}_2$ or $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ decomposed through several stages (Figs. 26-29). This could be attributed to the purity of the chemical that probably contained the mixture of the $\text{Hg-F}$ species. Humidity in the air also affects the further formation and transformation of compounds during heating. The decomposition of $\text{HgF}_2 \cdot 2\text{H}_2\text{O}$ could release $\text{HgO}$ and $\text{HF}$ when heated [34].

As already mentioned, released water could cause the transformation of $\text{HgF}_2$ into $\text{HgO}$ [32-35]. In general, many similarities were found between thermograms of $\text{HgF}_2$ and $\text{HgO}$ described below (Figs. 8-13 and 26-29).

For $\text{HgF}_2$ the major peak appeared at about 450°C or 430°C when purged with nitrogen or air, respectively (Figs. 26 and 27). Pure compound $\text{HgF}_2$ was also placed on a ceramic boat due to the possibility of fluorides reacting with silica (Fig. 28). Only one distinct peak at about 450°C was obtained and was consistent with the major peak of pure $\text{HgO}$ (red or yellow). The interactions of $\text{HgF}_2$ with the quartz boat are clearly evident by comparing Figs. 26-28.

$\text{HgF}_2$ mixed with $\text{SiO}_2$ peaks showed a similar pattern in nitrogen or air (Figs. 26 and 27). Two peaks could be seen in both cases, while the second peak was divided into two smaller peaks when purged with nitrogen. $\text{SiO}_2$ caused the shift of released peaks towards lower temperatures. During the heating $\text{HgF}_2$ probably transformed into $\text{HgO}$. Due to the interaction between $\text{SiO}_2$ and $\text{HF}$ that was released by the decomposition of $\text{HgFX}$ ($X = \text{OH}$, $F \cdot 2\text{H}_2\text{O}$), water was formed which could react with $\text{HgF}_2$, and, according to Eq. 12, transformed into $\text{HgO}$. The first small peak probably belongs to $\text{Hg}(0)$ formed during the preparation of the sample or the interaction with the substrate and its decomposition.

When $\text{HgF}_2$ was mixed with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, one main peak with a temperature of around 215°C could be seen when purged with nitrogen (Fig. 26). When purged with air, three peaks emerged, with the third peak being very low (Fig. 27). The substrate $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ contained inbound water which released during the heating process and probably caused the transformation of $\text{HgF}_2$ with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ into $\text{HgO}$. Interestingly, a very small peak could be seen at temperatures of around 430°C which was consistent with the pure $\text{HgO}$ compounds (Figs. 8, 9, 26 and 27).

Fig. 29 shows a MS thermogram of $\text{HgF}_2$ with different substrates. Although literature data also suggest sublimation of $\text{HgF}_2$ [32], results obtained using both methods (CV AAS and MS) indicate the decomposition through several stages.

A three step decomposition process was observed when $\text{HgF}_2$ was mixed with $\text{SiO}_2$, or $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, although the temperatures at which $\text{Hg}$ was released and their relative intensities were different (Fig. 29).

$\text{SiO}_2$ (Fig. 29) shows that the first peak probably belongs to elemental $\text{Hg}(0)$, similar to CV AAS. The second and third peak could represent $\text{HgO}$. The comparison of thermograms for pure $\text{HgO}$ mixed with $\text{SiO}_2$ and $\text{HgF}_2$ mixed with $\text{SiO}_2$ (Figs. 10, 13 and 29), shows a similar pattern. Thermograms that represent the release of $\text{HgO}$ mixed with $\text{SiO}_2$ have the highest second, and the lowest first peak, while the height of the third peak is dependent on the $\text{HgO}$ compound, where the red $\text{HgO}$ shows a higher peak (Figs. 10 and 13). $\text{HgF}_2$ mixed with $\text{SiO}_2$ shows that the third peak is the highest and probably represents the release of $\text{HgO}$ after it has already been fully transformed (Fig. 29).
HgF₂ mixed with CaSO₄ • 2H₂O shows that the first two peaks are higher compared to those thermograms of both HgO mixtures with CaSO₄ • 2H₂O, while the third is very low (Figs. 10, 13 and 29). The thermogram (Fig. 29) shows that the first two peaks probably represent released Hg during heating and formation of HgO whereby the third peak represents traces of HgO. Comparing HgF₂ and HgO mixed with CaSO₄ • 2H₂O (Figs. 10, 13 and 29) shows similarities in the temperature pattern of released Hg.

Thermograms obtained by CV AAS and MS show the connection between HgO and HgF₂ (Figs. 8-13 and 26-29). HgF₂ is very sensitive to the humidity and according to the experiment that was conducted on the ceramic boat (Fig. 28), the transformation into HgO occurred in the presence of air.

4 Conclusion

Experiments conducted during this research showed that the pyrolytic/combustion approach requires an understanding of the reactions of Hg compounds at higher temperatures. However, the mechanisms of such decompositions have not been studied in detail so far. The results of our work suggest that not only the carrier gas, its flow rate and substrate but also the heating rate and the material that is in contact with the samples affect the degradation pattern of Hg compounds. As a consequence, the heights and shapes of the peaks obtained, as well as their number and the temperature at which breakdown products appear, vary significantly for some compounds, particularly for the sulphates and fluoride. These processes are not fully understood as yet.

In the effort of reaching the long-term goal of this work, which was to develop a methodology for identification of Hg compounds in environmental and industrial solid materials, we realized that a number of experimental factors and, in particular the matrix itself, prevent the method to be applied to solid matrices of unknown composition. The spiking of matrices with pure compounds can help in the identification of Hg compounds and understanding the effects of the substrate on mercury temperature stability and Hg appearance in thermograms. The limitations, however, are related to the limited number of pure Hg compounds, which may not be representative of those contained in the solid matrix.

Although the primary goal was not fully achieved, we realized that the methodology developed in this study has a practical value. It provides reproducible and sensitive results of temperature dependent Hg decomposition pattern and can be used for the identification of temperature stability of mercury compounds contained in various substrates/materials. This can be applied in the identification of potential mercury release/emissions from materials subjected to elevated temperature treatments in various industries. Further fractionation experiments will, therefore, include mixtures of Hg compounds with different substrates, intended to resemble complex matrices for which temperature fractionation could provide useful information (for example coal, gypsum from industry, limestone, and materials used for adsorption at higher temperatures).

The potential of the method for separation and quantification of different Hg compounds in solid materials
Linguistic corrections of dr. A.R. Byrne are also acknowledged.

References


requires further investigations. Although the literature data available so far is useful, direct comparisons are difficult due to differences in the approaches used and the problems of interpretation when complex mixtures are being considered.

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