

THERMAL INVESTIGATIONS OF CEFADROXIL COMPLEXES WITH TRANSITION METALS Coupled TG-DSC and TG-FTIR techniques

*Renata Mrozek-Łyszczek**

Department of General Chemistry, Faculty of Chemistry, Maria Curie-Skłodowska University
M. C. Skłodowskiej Sq. 2, 20-031 Lublin, Poland

Abstract

The cefadroxil (Cef) complexes with transition divalent metals of the formula $MCef \cdot nH_2O$ (where $n=2$ for $M=Cu^{2+}$, Ni^{2+} , Zn^{2+} and $n=3$ for Co^{2+}) and $CdCef_{1.5} \cdot 4H_2O$ were prepared and characterized by elemental and infrared spectra. The thermal analysis of the investigated complexes in air atmosphere was carried out by means of simultaneous TG-DSC technique. During heating in air they lose bound water molecules and then decompose to oxides: Co_3O_4 , NiO, CuO, ZnO and CdO. The $CdCef_{1.5} \cdot 4H_2O$ complex forms probably an intermediate product Cd_2OSO_4 . The combined TG-FTIR technique was employed to study of decomposition pathway of the investigated complexes. The first mass loss step is the water loss of the complexes. Next, decomposition of cefadroxil ligand occurs with evolution of CO_2 and NH_3 . At slightly higher temperature COS is observed according to decomposition of cephem ring. Additionally, as decomposition gaseous products: HCN, HNCO (HOCN), H_2CNH , CO, SO_2 , hydrocarbons and carbonyl compounds were observed. The formation of metal sulfates is postulated as solid intermediate product of decomposition in the argon atmosphere.

Keywords: cefadroxil, gaseous products, metal complexes, TG-DSC, TG-FTIR analysis

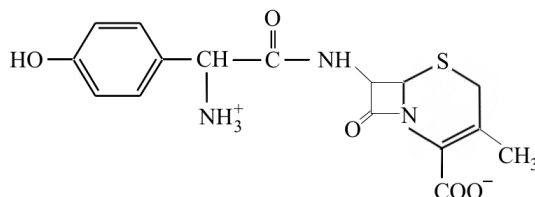
Introduction

An interaction between metal ions and pharmaceuticals is an attractive field of study. Metal ions are easily available for pharmaceuticals ligands because they appear in living system as free ions and they are bound to proteins, enzymes, nucleic acids and other bioligands [1, 2]. The metal complex formation is a simple way of modifying the properties of a drug. The adriamycin complex with Pt(II) is more active against certain tumor cells in comparison to parent drug while complex with Pd(II) has reduced antitumor activity [3]. The metal (II) complexes of cephalexin show better antibacterial activity than the antibiotics themselves [4]. In some cases metal ions are necessary for therapeutical activity of pharmaceuticals [5].

The most important class of drugs against infectious diseases caused by bacteria is β -lactamic antibiotics. The great families of such antibiotics form cephalosporins,

* Author for correspondence: E-mail: reniam@hermes.umcs.lublin.pl

which contain β -lactam moiety fused with a six-member ring. Cefadroxil Scheme 1 belongs to the first generation of cephalosporin antibiotics. The cefadroxil form in solution complexes of molar ratio 1:1 with following ions: Ca(II), Cu(II), Zn(II), Pb(II) and La(III) [6]. In the solid-state cefadroxil forms complexes with Cu(II) and Co(II) with molar ratio also 1:1 [7].



Scheme 1

This paper presents results from spectroscopic and thermal investigations of cefadroxil complexes with some divalent metals. The following metal ions: Cu^{2+} , Ni^{2+} , Zn^{2+} , Co^{2+} and Cd^{2+} have been chosen because they appear in human body. As can be seen from above mentioned literature, the metal complexes of cefadroxil may have better therapeutic activity in comparison to uncoordinated by metals antibiotic. In the future, the antibacterial activity of the studied complexes will be tested.

The TG-DSC method was used in order to determine the thermal behavior of the studied compounds in the air. The major goal of the application of coupled TG-FTIR technique was to give a possible decomposition path of metal complexes based on the composition of evolved gases. This method is widely used in the investigation of many drugs as well as substances of pharmacological interest [8–11].

Experimental

All chemicals were of analytical grade. Cefadroxil was obtained from Sigma. The metal nitrates and chlorides were obtained from P.O.CH. Gliwice.

The complexes have been obtained in the reaction of aqueous solution of sodium cefadroxil (pH=9; 2.744 mmol; 10 cm³) with solution of corresponding metal nitrate or chloride (2.744 mmol; 10 cm³) in a molar ratio 1:1. The solution of metal salt was added dropwise to solution of sodium salt at room temperature. After mixed, compounds precipitated immediately. The complexes have been washed with a little amount of water and acetone and dried at room temperature.

The percentage of C, H and N were obtained by means of elemental analysis using a PerkinElmer CHN 2400 apparatus. The transition metal contents were estimated by spectrometry of atomic absorption by using Spectrophotometer AA-880 (Varian).

The IR spectra of free cefadroxil and the studied compounds were recorded in the range 4000–400 cm⁻¹ on a Specord M80 spectrophotometer.

Thermal analysis of prepared compounds was carried out by the TG-DSC method using a Setsys 16/18 analyzer (Setaram). Samples about 7 mg were heated in ceramic

crucibles up to 1000°C at heating rate of 10°C min⁻¹ in dynamic air atmosphere ($v=0.75 \text{ dm}^3 \text{ h}^{-1}$).

The TG-FTIR coupled measurements have been carried out using a Netzsch TG 209 apparatus coupled with a Bruker FTIR IFS66 spectrophotometer. The sample of about 5 mg were heated in ceramic crucibles up to 600°C at a heating rate of 10°C min⁻¹ in flowing argon atmosphere.

X-ray powder diffraction patterns for the studied complexes and final solid product of thermal decomposition were recorded on a HZG 4 diffractometer. Measurements were taken over the range of $2\theta=2-70^\circ$ using Ni filtered CuK α radiation.

Results

The complexes of the formulae: CoCef·3H₂O, NiCef·2H₂O, CuCef·2H₂O, ZnCef·2H₂O and CdCef_{1.5}·4H₂O (where Cef-cefadroxil) were obtained. The cefadroxil ligand coordinates metal ions in the stoichiometric ratio 1:1. The analytical data of the investigated complexes are shown in Table 1. The powder patterns of the investigated complexes (with exception of cadmium complex) indicate that they are amorphous.

Table 1 Elemental analysis data

Complex	C/%		H/%		N/%		M/%	
	calc.	found	calc.	found	calc.	found	calc.	found
CoCef·3H ₂ O	40.30	40.03	4.83	4.62	8.73	8.82	12.37	11.83
NiCef·2H ₂ O	41.88	41.26	4.58	4.94	9.16	9.04	12.80	13.05
CuCef·2H ₂ O	41.47	41.55	4.53	4.52	9.07	9.13	13.74	13.99
ZnCef·2H ₂ O	41.34	41.92	4.52	4.57	9.04	9.17	14.08	13.82
CdCef _{1.5} ·4H ₂ O	39.48	40.22	4.59	4.61	8.64	8.73	15.41	15.62



Spectroscopic description

Evidence for complex formation was obtained by comparing the infrared spectra of the free cefadroxil and complexes in the region of 4000–400 cm⁻¹. The most characteristic bands and their assignments are given in Table 2. The spectra of cobalt, nickel, copper and zinc complexes are very similar to each other. The IR spectrum of cadmium complex looks entirely different. The IR spectrum of cefadroxil shows in the wavenumber region 3600–2400 cm⁻¹ broad band with many submaxima. The sharp band at 3505 cm⁻¹ is due to stretching vibrations of ‘free’ OH group of hydroxyphenyl from cefadroxil [7]. This band disappeared in spectra of metal complexes that may point to ionization of the hydroxyl group. In the spectrum of cefadroxil, the band at 3273 cm⁻¹ is assigned to stretching vibration of N–H of hydrogen bound amide group [12]. In the investigated complexes in this wavenumber region only a very broad band with a maximum at about 3200 cm⁻¹ appears. This band

Table 2 Most important IR absorption bands (in cm^{-1}) of free cefadroxil and its metal(II) complexes

Compound	νOH (free)	$\nu\text{N-H}$ νNH_3^+	$\nu\text{O-H}$ (hydrogen bound)	$\nu\text{C=O}$ (β -lactam)	$\nu\text{C=O}+\nu\text{CN}$ (amide I)	$\nu\text{CN}+\beta\text{NH}$ (amide II); $\nu_{\text{asym}} \text{COO}$	$\nu_{\text{sym}} \text{COO}$
cefadroxil	3505	3273 2600	–	1758	1686	1650; 1517 1563	1399
CoCef \cdot 3H ₂ O	–	–	3406	1758	–	1612	1369
NiCef \cdot 2H ₂ O	–	–	3275	1759	–	1594	1365
CuCef \cdot 2H ₂ O	–	–	3248	1760	–	1592	1360
ZnCef \cdot 2H ₂ O	–	–	3273	1761	–	1612	1382
CdCef \cdot _{1,5} 4H ₂ O	3536	3400	3270	1756	1664	1584	1420

Cef = C₁₆H₁₇N₃O₅S

is assigned to stretching vibrations of OH group from hydrogen bonded water molecules [13]. The band of NH_3^+ group at 2600 cm^{-1} in cefadroxil spectrum disappeared in spectra of metal complexes.

The infrared spectra of β -lactam antibiotics exhibit the characteristic band arising from stretching vibrations of the carbonyl group of β -lactam ring [14]. In the free cefadroxil spectrum vibration of this mode appears at 1758 cm^{-1} . This band appears also in all studied complexes almost at the same wavenumber. It may suggest that the carbonyl oxygen atom from β -lactam ring is not engaged in metal binding. Disappearing of such band is indicative for the participation of β -lactam in metal coordination or hydrolysis of β -lactam ring [15]. Another characteristic group from cefadroxil ligand is an amide group from side chain. The band observed at 1686 cm^{-1} is coming from stretching vibrations of amide carbonyl group [16]. This band vanished in metal complexes with the exception of $\text{CdCef}_{1.5}\cdot 4\text{H}_2\text{O}$. Because of zwitterionic character of cefadroxil the spectrum of free ligand shows bands of antisymmetric (ν_{as}) and symmetric (ν_{s}) vibrations of carboxylate group at 1563 and 1399 cm^{-1} , respectively [4]. The bands assigned to $\nu_{\text{as}}\text{COO}$ overlapped with II amide band (βNH , νCN). In spectra of metal complexes $\nu_{\text{as}}\text{COO}$ band is shifted towards higher wavenumber than $\nu_{\text{sym}}\text{COO}$ towards lower wavenumber. This fact suggests interaction between metal ions and carboxylate group of cefadroxil [17]. Based on the analysis of infrared spectra coordination through amide group and carboxylate group is proposed. Probably, the studied complexes have polymeric structure. For cadmium complex entirely different mode of coordination is observed. The principle difference in comparison to remaining spectra is present of stretching vibration of carbonyl group at 1664 cm^{-1} . The antisymmetric and symmetric stretching vibrations of carboxylate group are shifted towards frequencies 1568 and 1420 cm^{-1} , respectively. It may point to coordination only by carboxylate group while carbonyl group from amide group is not engaged in coordination.

Thermal description

Thermal behavior of metal complexes has been studied by using TG-DSC method and coupled TG-FTIR system in order to investigate evolved gases. For understanding the decomposition pathway of metal complexes better the degradation of free cefadroxil has been studied.

Description of cefadroxil decomposition

The TG and DSC curves of cefadroxil obtained during heating in air are shown in Fig. 1. The first mass loss on the thermogravimetric curve occurring in the $70\text{--}180^\circ\text{C}$ range corresponds to the loss of 1 mol water molecule. The dehydration is accompanied by a broad endothermic peak according to the loss of an adsorbed water molecule. In interval $200\text{--}600^\circ\text{C}$ decomposition with burning of cefadroxil is observed. At 207°C on the DSC curve very sharp exothermic peak is observed. At the same temperature on the TG curve a rapid loss of mass is recorded that can be attributed to releasing of 1 mol of NH_3 and 1 mol of CO_2 (16.8%). The second exothermic effect is superimposition of processes connected with degradation and oxidation.

Stacked plot of the infrared spectra of the evolved gases for cefadroxil is given in Fig. 2. In the coupled TG-FTIR experiment water molecules were detected as the first product of cefadroxil thermal decomposition. FTIR spectra recorded to 200°C show bands in the wavenumber ranges 3750–3500 and 1900–1300 cm^{-1} corresponding to stretching and deformation vibrations of H_2O molecules, respectively [18, 19]. Next complex degradation process occurs with releasing many gaseous products. Carbon dioxide is evolved at all temperature from 200 to 600°C. It gives characteristic absorption bands in frequencies ranges: 2300–2250 and 750–600 cm^{-1} due to valence and deformation vibrations, respectively. On the carbon dioxide bands overlapped vibrations from cyanic acid, which give band at 2280 cm^{-1} . In the temperature range 200–440°C besides CO_2 and weak band H_2O there are observed evolution of COS , NH_3 and SO_2 . The double-band at 2071 and 2040 cm^{-1} has been assigned to stretching vibrations of COS molecules [20, 21]. Ammonia gives easy detectable double-peak bands with maxima at 966 and 932 cm^{-1} arising from deformation vibra-

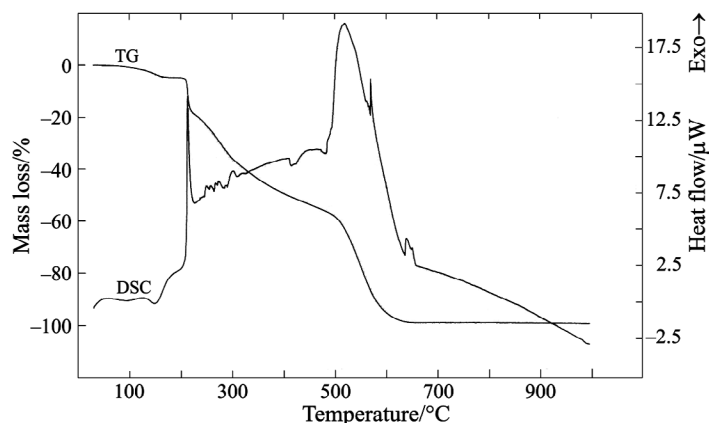


Fig. 1 TG and DSC curves of cefadroxil (in air)

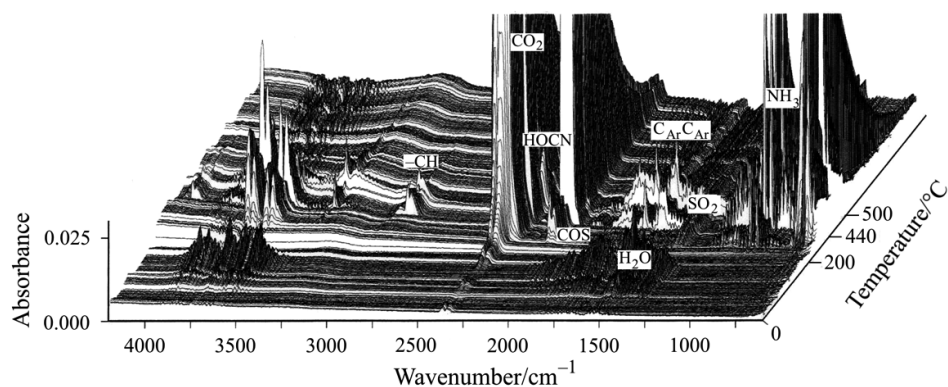


Fig. 2 Stacked plot of the FTIR spectra of the evolved gases for the cefadroxil

tions. The bands at 1374, 1361, 1339 cm^{-1} have been recognized as arising from SO_2 molecule [22]. The TG-FTIR spectra collected in the temperature range 440–500°C near bands raised from CO_2 , NH_3 , HCN , HOCN and COS show presence of absorption peaks at 2926, 1626, 1516, 1542 and 1533 cm^{-1} . These bands were attributed to aromatic species of degradation products. The band at 2926 cm^{-1} corresponds to stretching vibrations of C–H group [23]. The peaks at 1516, 1542 and 1533 cm^{-1} were assigned to stretching vibration $\text{C}_{\text{Ar}}\text{C}_{\text{Ar}}$ in aromatic ring [24].

The thermal decomposition (in air) of metal complexes

The TG and DSC curves are shown in Figs 3–7. All the investigated complexes are stable up to about 50°C. Further heating of complexes in air atmosphere as well as in argon resulting in dehydration process, which occurs in about 50–150°C temperature range. Mass loss on the TG curve is accompanied by weak endothermic effect on the DSC curve. This fact may point to only weak bonding of water molecules in structures of complexes. Further heating of unstable anhydrous complexes causes decomposition. As contrasted with remaining compounds only anhydrous $\text{CdCef}_{1.5}$ is stable (up to 191°C). The experimental and expected mass losses are given in Table 3.

Table 3 Thermogravimetric data obtained during heating complexes in air atmosphere

Compound	$T_1/^\circ\text{C}$	Mass loss/%		$T_2/^\circ\text{C}$	Mass loss/%		Residue
		found	calc.		found	calc.	
$\text{CoCef}\cdot 3\text{H}_2\text{O}$	50–150	11.22	11.34	150–530	84.38	83.15	Co_3O_4
$\text{NiCef}\cdot 2\text{H}_2\text{O}$	40–145	8.05	7.85	145–555	84.31	85.05	NiO
$\text{CuCef}\cdot 2\text{H}_2\text{O}$	48–160	8.15	7.78	160–428	81.23	82.83	CuO
$\text{ZnCef}\cdot 2\text{H}_2\text{O}$	51–140	7.68	7.75	140–630	75.10	74.81	ZnO
$\text{CdCef}_{1.5}\cdot 4\text{H}_2\text{O}$	48–148	9.35	9.87	191–623	81.18	82.40	CdO

In oxidative air atmosphere degradation of organic ligand is accompanied by strong exothermic effect connected with burning of organic ligand. The degradation process is intricate and is not possible to distinguish intermediate solid products. Only in the case of $\text{CdCef}_{1.5}\cdot 4\text{H}_2\text{O}$ compound, the TG curve shows distinct mass loss (46.17%), which may be attributed to Cd_2OSO_4 formation (Fig. 7). The solid residues obtained during thermal decomposition of complexes are suitable metal oxides: Co_3O_4 , NiO, CuO, ZnO and CdO. Their compositions have been confirmed by X-ray diffraction measurement. The diffraction patterns of obtained residues have been compared with reference patterns.

The thermal decomposition of the studied complexes in argon atmosphere has been investigated using coupled TG-FTIR technique. The data obtained from analysis of gaseous products of thermal decomposition point to some differences in decomposition way of complexes. Therefore TG-FTIR spectra will be described apparently for cefadroxil and its metal complexes. Gaseous products observed during decomposition of metal

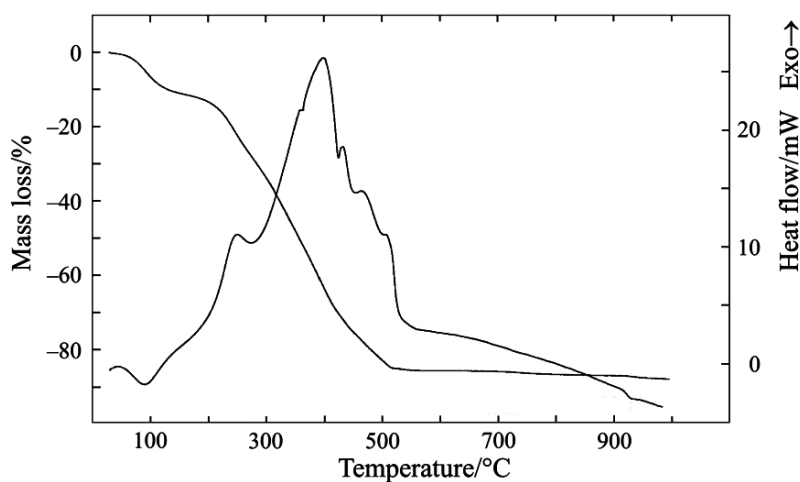


Fig. 3 TG and DSC curves of $\text{CoCef}\cdot 3\text{H}_2\text{O}$ (in air)

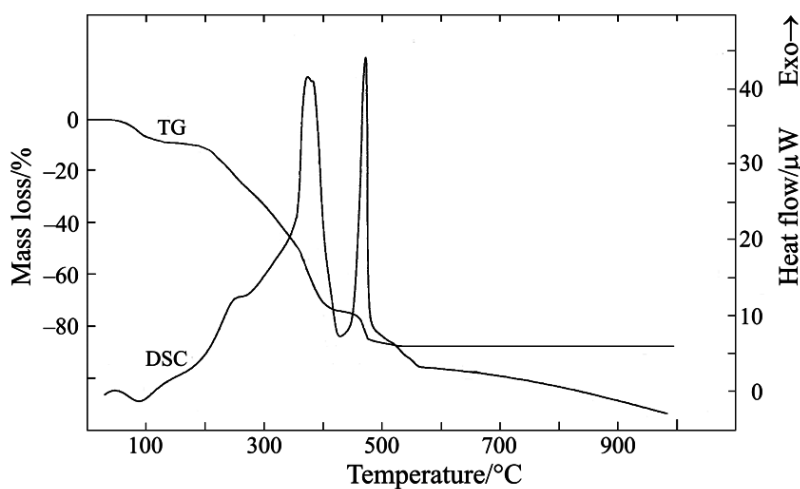


Fig. 4 TG and DSC curves of $\text{NiCef}\cdot 2\text{H}_2\text{O}$ (in air)

complexes and cefadroxil are given in Table 4. The figure of FTIR spectra of evolved gas products is given only for $\text{CoCef}\cdot 3\text{H}_2\text{O}$ as the most representative among metal complexes, which behave relatively similar during thermal decomposition.

TG-FTIR spectra of $\text{CoCef}\cdot 3\text{H}_2\text{O}$

The FTIR spectra recorded to 170°C range show only weak bands from water molecules. At a slightly higher temperature characteristic bands from stretching and deformation vibrations of carbon dioxide are observed according to decomposition of

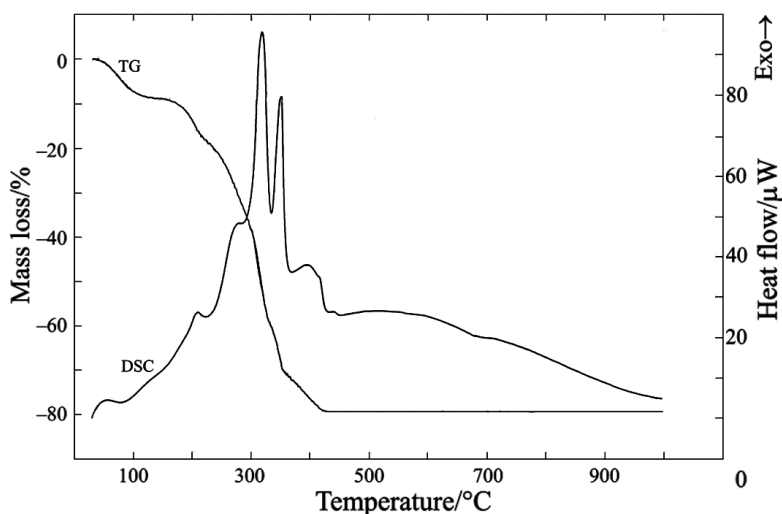


Fig. 5 TG and DSC curves of $\text{CuCef}\cdot 2\text{H}_2\text{O}$ (in air)

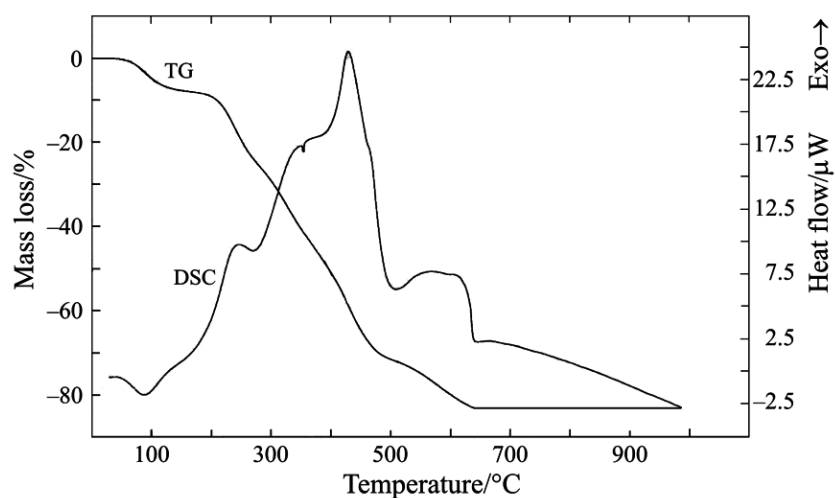


Fig. 6 TG and DSC curves of $\text{ZnCef}\cdot 2\text{H}_2\text{O}$ (in air)

organic ligand. At the same temperature as the product of decomposition ammonia is produced. Upon further heating the opening of cephem ring appears. The FTIR spectra show bands with maxima at 2070 ; 2050 cm^{-1} which are attributed to vibrations of COS and additionally are present absorption peaks at 1375 , 1359 , 1341 cm^{-1} recognized as asymmetric stretching vibrations of SO_2 . Additionally, a band at 2280 cm^{-1} appears attributed to stretching $\text{C}\equiv\text{N}$ vibrations from cyanic acid [25]. The highest intensity of evolution of these gases is observed at 320°C . Moreover, at the same time

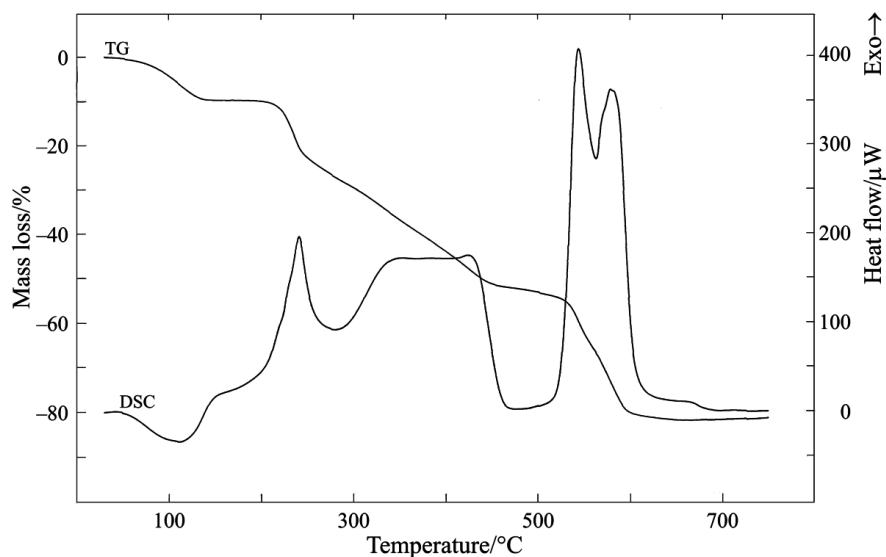


Fig. 7 TG and DSC curves of CdCef_{1.5}·4H₂O (in air)

Table 4 Identification of FTIR peaks observed in various temperature ranges during heating of free ligand and metal complexes

Compound	T/°C	Gases (or groups)
Cefadroxil	to 200	H ₂ O
	200–440	H ₂ O, NH ₃ , CO ₂ , COS, SO ₂ , HOCN
	440–500	CO ₂ , NH ₃ , HCN, HOCN, COS, –CH, C _{Ar} C _{Ar}
CoCef·3H ₂ O	to 170	H ₂ O
	170–320	CO ₂ , NH ₃ , COS, SO ₂ , HOCN, –CH, –C=O, –C=N–, C _{Ar} C _{Ar}
	>320	CO ₂ , NH ₃ , SO ₂ , HOCN, CO
NiCef·2H ₂ O	to 180	H ₂ O
	180–400	CO ₂ , COS, HCN, HNCO, NH ₃ , C _{Ar} C _{Ar} , –C=O, –C=N–, SO ₂
	400–600	CO ₂ , CO, NH ₃ , HNCO, SO ₂
	600	CO ₂ , SO ₂ , NH ₃ , –SH
CuCef·2H ₂ O	to 200	H ₂ O
	200–490	H ₂ O, CO ₂ , NH ₃ , COS, HNCO, HCN, –CH–C _{Ar} C _{Ar} , CH ₄
	>490	CO ₂ , CO, SO ₂ , HNCO, NH ₃
ZnCef·2H ₂ O	to 180	H ₂ O
	180–370	H ₂ O, CO ₂ , NH ₃ , COS, HCN, SO ₂ , HOCN
	370–420	CO, NH ₃ , CO ₂ , SO ₂
CdCef _{1.5} ·4H ₂ O	to 120	H ₂ O
	230–460	CO ₂ , HOCN, NH ₃ , –C=N–, HCOOH, –CH
	460	CO ₂ , NH ₃ , COS, SO ₂

bands at 2974, 1734, 1626 and 1508 cm^{-1} were recorded. The absorption peak at 2974 cm^{-1} was assigned to stretching vibrations of C–H due to evolution of hydrocarbons or their derivatives. The band at 1505 cm^{-1} was recognized as aromatic ring vibrations. The band at 1626 cm^{-1} was attributed to stretching vibrations of –C=N– from methanimine [26]. Probably also some carbonyl compounds are evaluated due to stretching vibration of –C=O group observed at 1734 cm^{-1} [27]. Upon 320°C the absorption bands from COS and hydrocarbons disappeared. On the contrary beside HOCN, CO_2 and NH_3 gases evolution are present very indicative and strong bands from SO_2 and CO. Carbon monoxide give easily detectable double-bands in the 2250–2050 cm^{-1} region (Fig. 8).

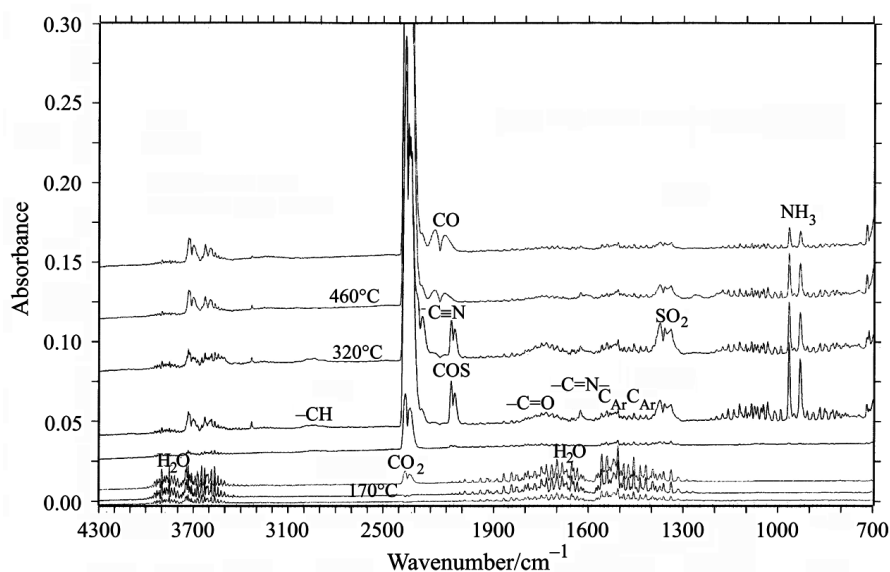


Fig. 8 FTIR spectra of evolved gas products of $\text{CoCef}\cdot 3\text{H}_2\text{O}$

TG-FTIR spectra of $\text{NiCef}\cdot 2\text{H}_2\text{O}$

Based on the analysis of TG-FTIR spectra of evolved gases formed during complex heating, a four-step decomposition process can be proposed. At first, at 180°C only water molecules have been detected. In the 180–400°C temperature range strong bands from CO_2 , HCN, HONC, COS, SO_2 and NH_3 were recorded. At the same temperature, aromatic hydrocarbons, methanimine and carbonyl compounds are released due to the appearance of bands at 2947, 1736, 1626, 1533 cm^{-1} , respectively. Upon 400°C bands from COS disappear and the produced gases are: SO_2 , CO_2 , HONC, CO and NH_3 . The FTIR spectrum recorded at 600°C shows weak absorption band at 2500 cm^{-1} assigned to S–H vibration [28], medium bands from NH_3 and CO_2 and very intense bands from stretching asymmetric and symmetric vibrations of SO_2 in ranges 1370, 1350 and 1150, 1140 cm^{-1} , respectively.

The TG-FTIR spectra of CuCef·2H₂O

Similarly as in other complexes the first step of decomposition is dehydration. After that degradation of complex with evolution of gaseous products appears. The FTIR spectra collected in the 200–490°C temperature range show evolution of H₂O, HOCN, CO₂, NH₃ and COS. Beside them there are bands at 3211 and 713 cm⁻¹ assigned to vibrations from HCN [29]. At the same time methane is evolved due to presence of very diagnostic band at 3016 cm⁻¹ [13]. Appearance of absorption bands at 2931 and 1510 cm⁻¹ is connected with stretching vibrations of C–H group and aromatic ring vibrations C_{Ar}C_{Ar}, respectively. It points to the evolution of some aromatic hydrocarbons. Spectra of evolved gases recorded upon 490°C show bands attributed to CO₂, CO, HOCN, SO₂ and traces of NH₃.

The TG-FTIR spectra of ZnCef·2H₂O

During heating to 180°C, the stretching and deformation vibrations of water molecules are only observed. In the temperature interval 180–370°C the following gaseous products of decomposition appear: H₂O, CO₂, NH₃, COS, SO₂ and HCN. Additionally, cyanic acid (HOCN) was recognized according to the appearance of stretching vibrations of C≡N group at 2253 cm⁻¹ and vibrations from OH group at 3560 and 1261 cm⁻¹. The stretching vibrations C–H at 3250 cm⁻¹ and deformation vibrations at 712 cm⁻¹ were attributed to HCN. The most intensity of releasing the above mention gases (except ammonia) is observed at 370°C. At 420°C the double peak arisen from vibrations of COS disappeared whereas very diagnostic bands of CO molecule are emerged. Additionally, at the same temperature the highest intensity of ammonia emission is observed. Further heating causes further NH₃, CO₂ and SO₂ evolution.

The TG-FTIR spectra of CdCef_{1.5}·4H₂O

According to the dehydration process up to 120°C water molecules are observed on the FTIR spectra. Above 230°C decomposition of anhydrous complex appears. At first, carbon dioxide and ammonia are observed as a product of decomposition. Next, decomposition of cephem ring appears that is reflected in releasing of COS molecules. Releasing carbonyl sulfide coincide with formation of HOCN. Cyanic acid gives characteristic bands: at 3597 and 1261 cm⁻¹ due to stretching and deformations vibrations of OH group, respectively and stretching vibrations of C≡N group at 2284 cm⁻¹ [25]. Additionally, on the FTIR spectra bands are shown at: 3580, 1797, 1780 and 1170 cm⁻¹ assigned to: stretching vibrations of OH group, stretching vibrations of –C=O group and stretching vibrations of –C–O group, respectively. Such vibrations can be produced by evolved formic acid [30]. Also absorption peak at 1626 cm⁻¹ is observed as driving from –C=N– vibrations. Traces of some hydrocarbons can be observed according to weak band at 2927 cm⁻¹. At slightly higher temperature bands from formic acid disappeared and increase of evolution of CO₂, NH₃ and COS are observed. Upon 460°C carbonyl sulfide is not released. Among the gaseous products of decomposition only absorption bands from NH₃, CO₂, CO and SO₂ are observed as can be seen from Fig. 9.

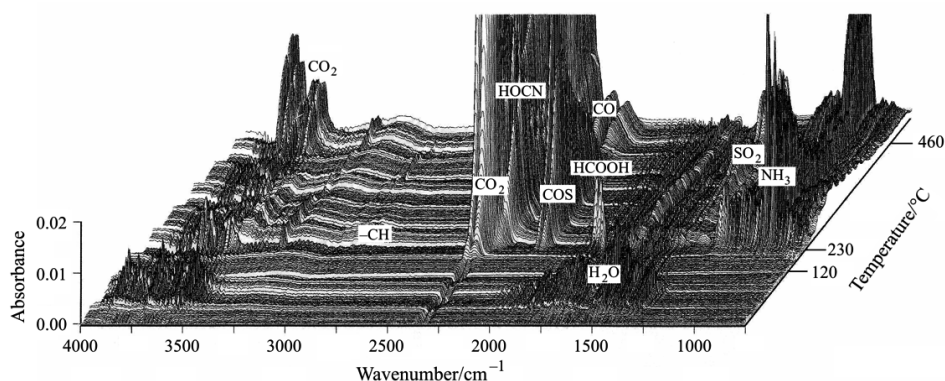


Fig. 9 Stacked plot of FTIR spectra of evolved gas products of CdCef_{1.5}·4H₂O

Conclusions

- The investigated complexes are stable up to 50°C in air as well as in argon atmosphere.
- From TG data obtained in air atmosphere two main stages of decomposition can be distinguished. In the first step, water molecules are evolved. When temperature increased to about 150°C immediately burning of organic ligand appears. The metal oxides (MO or M₃O₄) are formed as final stable product of decomposition.
- The CdCef_{1.5} bands H₂O complex shows different thermal behavior. In comparison to other compounds during heating, the stable anhydrous complex is formed. Additionally, formation of intermediate product of decomposition (Cd₂OSO₄) is postulated.
- The TG-FTIR spectra of free cefadroxil as well as complexes point to multi-stage decomposition in argon atmosphere.
- Cefadroxil decomposes in three stages: a) evolution of weakly bound water molecule; b) releasing of CO₂ and NH₃ with opening of cephem ring (evolution of carbonyl sulfide and sulfur dioxide); c) further decomposition with releasing of aromatic species and HCN, HOCN and methanimine.
- Based on the nature of evolved gaseous products, the way of the decomposition of complexes has been proposed. During heating three main stages can be distinguished: a) dehydration process (evolution of water molecules); b) evolution of gaseous products as: CO₂, NH₃, HCN, HNCN (HOCN), COS, SO₂ (connected with degradation of dihydrothiazine ring), hydrocarbons, carbonyl compounds; c) evolution of CO and SO₂. In comparison to free cefadroxil carbon monoxide is produced during complexes heating. Additionally, in the high temperature the increasing of intensity of SO₂ evolution is observed. It may be explained by the fact of metal sulfate formation during the decomposition process, which at higher temperature (argon atmosphere) is reduced by carbon to SO₂.
- The temperature of evolution of hydrocarbons and aromatic compounds in metal complexes is relatively lower in comparison to free ligand.

- The decomposition pathway confirms also differences in mode of bonding metal by cefadroxil. Only in the case of $\text{CdCef}_{1.5} \cdot 4\text{H}_2\text{O}$ among gaseous products formic acid is observed as driving probably from decomposition of side chain.

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