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Thermochemical properties of two nitrothiophene derivatives

2-acetyl-5-nitrothiophene and 5-nitro-2-thiophenecarboxaldehyde

Manuel A. V. Ribeiro da Silva · Ana Filipa L. O. M. Santos

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Abstract This article reports the values of the standard (p^{o} = 0.1 MPa) molar enthalpies of formation, in the gaseous phase, $\Delta_{\mathrm{f}}H^{\mathrm{o}}_{\mathrm{m}}(\mathrm{g})$, at $T = 298.15$ K, of 2-acetyl-5-nitrothiophene and 5-nitro-2-thiophenecarboxaldehyde as $-(48.8 \pm 1.6)$ and (4.4 ± 1.3) kJ mol^{-1}, respectively. These values were derived from experimental thermodynamic parameters, namely, the standard ($p^{\mathrm{o}} = 0.1$ MPa) molar enthalpies of formation, in the crystalline phase, $\Delta_{\mathrm{f}}H^{\mathrm{o}}_{\mathrm{m}}(\mathrm{cr})$, at $T = 298.15$ K, obtained from the standard molar enthalpies of combustion, $\Delta_{\mathrm{c}}H^{\mathrm{o}}_{\mathrm{m}}$, measured by rotating bomb combustion calorimetry, and from the standard molar enthalpies of sublimation, at $T = 298.15$ K, determined from the temperature–vapour pressure dependence, obtained by the Knudsen mass loss effusion method. The results are interpreted in terms of enthalpic increments and the enthalpic contribution of the nitro group in the substituted thiophene ring is compared with the same contribution in other structurally similar compounds.

Keywords 2-Acetyl-5-nitrothiophene · 5-nitro-2-thiophenecarboxaldehyde · Combustion calorimetry · Knudsen mass loss effusion method · Enthalpy of combustion · Enthalpy of formation · Enthalpy of sublimation · Thiophene

Introduction

The structure and energetics of the molecules are two of the most important properties of compounds, being, therefore, two fundamental concepts in chemistry. The main purpose of thermochemistry lies in obtaining the thermochemical properties of the species, especially the enthalpies of formation and bond dissociation enthalpies. They are important in establishing relationships between the energetics of inter and intramolecular chemical bonds, their structural properties and reactivity. These thermochemical parameters are fundamental in several science fields, such as medicine, pharmaceutical industry, biology, petrochemistry, environmental, and industrial chemistry.

Nitrothiophenes are compounds that have been used as antibacterial, antiprotozoal and anthelminthic drugs in man and animals and they were found to be carcinogenic [1]. Wang et al. [1] showed that 2-acetyl-5-nitrothiophene was mutagenic in *Salmonella typhimurium* TA 98 and TA 100 and since it is mutagenic on microorganisms, it may be potential hazard for man. Further more, this compound is used in the synthesis of certain five-membered sulphur-containing heteroaromatic diketo acid derivatives which are potent inhibitors of HIV integrase [2] and it is also used in the synthesis of Alzheimer's disease imaging agents [3]. 5-Nitro-2-thiophenecarboxaldehyde and 2-acetyl-5-nitrothiophene are used in the preparation of 5-nitrothiophenes prodrugs of combretastatatin A-4, an antineoplasic therapeutic compound [4], and 5-nitrothiophene derivatives are also employed in the synthesis of Ranbezolid analogues, a molecule active against Gram-positive pathogens, which shows antibacterial activity, in vitro [5].

The crystal structure of 5-nitro-2-thiophenecarboxaldehyde was determined at $T = 100$ K, by McBurney et al. [6]. The crystalline system is orthorhombic, space group $Pna2_1$ and the molecule is essentially planar; however, the nitro group and the aldehyde group are 8.37° and 8.5°, respectively, outside the plane of the thiophene ring.

M. A. V. Ribeiro da Silva (✉) · A. F. L. O. M. Santos
Department of Chemistry, Faculty of Science,
Centro de Investigação em Química, University of Porto,
Rua do Campo Alegre, 687, 4169-007 Porto, Portugal
e-mail: risilva@fc.up.pt

5-Nitro-2-thiophenecarboxaldehyde 2-Acetyl-5-nitrothiophene

Fig. 1 Structural formula of the compounds studied in this work

In the crystal structure, molecules are connected by weak C–H···O hydrogen bonds.

As part of our interest on the thermochemistry of thiophene derivatives [7–17], a research program has being carried out in our Research Group, which aims the study of the enthalpic effects of the introduction of different substituents into the aromatic thiophene ring, so we have now studied the energetics of two nitrothiophene derivatives, namely 2-acetyl-5-nitrothiophene and 5-nitro-2-thiophenecarboxaldehyde.

This article presents the standard ($p^\circ = 0.1$ MPa) molar enthalpies of formation, in the crystalline phase, at $T = 298.15$ K, of the title nitrothiophene derivatives, obtained from the standard molar energies of combustion, in oxygen, measured by rotating bomb combustion calorimetry. The respective standard molar enthalpies of sublimation, $T = 298.15$ K, were calculated by the Clausius–Clapeyron equation, from the temperature dependence of the vapour pressures of these compounds, determined by Knudsen effusion mass-loss technique. These data, together with the respective standard molar enthalpies of formation, in the crystalline phase, enabled us to calculate the standard molar enthalpies of formation, in the gaseous state, of the two compounds depicted in Fig. 1.

Experimental

Materials

Compounds and purity control

2-Acetyl-5-nitrothiophene [CAS 39565-00-9] was obtained commercially from Alfa Aesar, whereas 5-nitro-2-thiophenecarboxaldehyde [CAS 4521-33-9] was purchased from Sigma-Aldrich Chemical Co. with mass fraction purities of 0.98 and 0.99, respectively. The two compounds, which are solid at room temperature, were purified by successive vacuum sublimations. Purity control of the nitrothiophene derivatives was assessed from gas liquid chromatography and differential scanning calorimetry, being found to be greater than 0.9999.

The benzoic acid used in the calibration of the bomb was the NIST Standard Reference Material 39i. Thianthrene ($C_{12}H_8S_2$), used as reference material for rotating bomb combustion calorimetry of organosulphur compounds, was supplied by Sigma-Aldrich Chemical Co., with a mass fraction purity of 0.99 and further purified by zone melting.

In the case of 5-nitro-2-thiophenecarboxaldehyde, the specific density used to calculate the true mass from apparent mass in air was, $\rho = 1.701$ g cm^{-3} [6], whereas for 2-acetyl-5-nitrothiophene the value used, $\rho = 1.486$ g cm^{-3}, was determined from the ratio mass/volume of pellets of the compound (made in vacuum, with an applied pressure of 10^5 kg cm^{-2}).

Methods

Combustion calorimetry

The energies of combustion of the two nitrothiophene derivatives were measured with an isoperibolic rotating-bomb calorimeter, already described in literature [7, 18, 19]. The bomb is internally lined with tantalum and all the internal fittings are also made from tantalum. It has an internal volume of 0.329 dm^3. In each experiment, water was added to the calorimeter from a weighed acrylic vessel and corrections were made to the energy equivalent of the calorimeter whenever the mass of water used was different from the reference mass of 3965.0 g. The calorimeter temperatures were measured to $\pm(1 \times 10^{-4})$ K, in time intervals of 10 s, using a quartz thermometer (Hewlett Packard HP 2804A) interfaced to a microcomputer programmed to compute the adiabatic temperature change. In the fore-period, 125 readings are taken, whereas in the main period the number of readings is 100, followed by 125 readings in the after-period. For all experiments, the ignition was made so that the final temperatures were, as close as possible to $T = 298.15$ K. The rotating mechanism allows simultaneous axial and end-over-end rotation of the bomb. The frictional work of bomb rotation was automatically included in the correction for heat exchange and work of water stirring, by using the procedure described by Good et al. [20].

Data acquisition and control of the calorimeter temperature was performed by means of LABTERMO program [21].

The energy equivalent of the calorimeter was determined by calibration experiments, without rotation of the bomb, from the combustion of benzoic acid NIST Thermochemical Standard 39i, with a certified massic energy of combustion, under bomb conditions, of $-(26434) \pm 3$ J g^{-1}, as described previously [22]. From 10 calibration experiments, that were made in oxygen at $p = 3.04$ MPa with 1.00 cm^3 of deionised water added to the bomb, the value of the energy equivalent of the calorimeter was found to be $\varepsilon(\text{calor}) = (20369.0 \pm 2.3)$ J K^{-1} (0.011%), for an average mass of water of 3965.0 g added to the calorimeter; the quoted uncertainty is the standard deviation of the mean.

Samples of each compound, in pellet form, were ignited in oxygen at a pressure of 3.04 MPa with a volume of 15.00 cm^3 of deionised water added to the bomb. The procedure described by Waddington et al. [23], for combustion calorimetry of organosulphur compounds, was followed.

The electrical energy for ignition was determined from the change in potential difference across a 1281 μF condenser discharged through a platinum wire ($\phi = 0.05$ mm, Goodfellow, mass fraction 0.9999).

The massic energy of combustion of the cotton thread fuse, with an empirical formula of $CH_{1.686}O_{0.843}$, is $\Delta_c u^\circ = -16240 \text{J g}^{-1}$ [20]. The amount of nitric acid was determined by the Devarda's alloy method [24] and corrections were based on $-59.7 \text{ kJ mol}^{-1}$ for the standard molar energy of formation in which 0.1 mol dm^{-3} $HNO_3(aq)$ is formed from $O_2(g)$, $N_2(g)$, and $H_2O(l)$ [25].

For each compound, $(\partial u/\partial p)_T$, at $T = 298.15$ K, was assumed to be $-0.2 \text{ J g}^{-1} \text{ MPa}^{-1}$, a typical value for organic compounds [26]. Standard state corrections, ΔU_Σ, were calculated by the procedures given by Hubbard et al. [27] and by Good and Scott [28].

The water added to the calorimetric vessel was weighed with a Mettler PC 8000 balance, sensitivity $\pm(1 \times 10^{-1})$ g and the necessary weighings for the combustion experiments were made in a Mettler Toledo AG 245 balance, sensitivity $\pm(1 \times 10^{-5})$ g.

The relative atomic masses used for the elements were those recommended by the IUPAC Commission in 2005 [29].

Vapour pressure measurements

The vapour pressures of the crystals, at several temperatures, were measured in a Knudsen effusion apparatus which enables the simultaneous operation of nine aluminium effusion cells at three different temperatures, using the mass-loss Knudsen effusion technique. A full description of the main features of the apparatus, the measuring procedure, technique and the results obtained with five test substances (benzoic acid, phenanthrene, anthracene, benzanthrone and 1,3,5-triphenylbenzene) have been reported in a previous paper [30]. The nine effusion cells are contained in cylindrical holes inside three aluminium blocks, three cells per block. Each block is kept at a constant temperature, different from the other two blocks.

For each compound, the measurements were extended through a chosen temperature interval corresponding to measured vapour pressures in the range 0.1 to 1.0 Pa. In each effusion experiment the loss of mass, Δm, of the samples, during a convenient effusion time period t, is determined by weighing the effusion cells to ± 0.01 mg, before and after the effusion period in a system evacuated to a pressure near (1×10^{-4}) Pa. At the temperature T of the experiment, the vapour pressure p is calculated by the Knudsen equation

$$p = (\Delta m / A_o w_o t) \cdot (2\pi RT/M)^{1/2}, \tag{1}$$

where M is the molar mass of the effusing vapour, R is the gas constant, A_o is the area of the effusion hole and w_o is the respective Clausing factor calculated by Eq. 2, where l is the thickness of the effusion hole and r its radius:

$$w_o = \{1 + (3l/8r)\}^{-1}. \tag{2}$$

There are three different groups of effusion cells, according to their different areas of effusion orifices: series A (small orifices; $A_o \approx 0.5 \text{ mm}^2$), series B (medium orifices; $A_o \approx 0.8 \text{ mm}^2$), series C (large orifices; $A_o \approx 1.1 \text{ mm}^2$). There was a 2 years gap between the 5-nitro-2-thiophenecarboxaldehyde Knudsen experiments and the ones of 2-acetyl-5-nitrothiophene. During this period of time, some effusion orifices suffered some damage and had to be replaced. For the study of 5-nitro-2-thiophenecarboxaldehyde, the areas and Clausing factors of the effusion orifices, in the platinum foil of $l =$ 0.0125 mm thickness, are, respectively, 0.502 mm^2 and 0.988 (oven 1, small orifice), 0.774 mm^2 and 0.991 (oven 1, medium orifice), 1.116 mm^2 and 0.992 (oven 1, large orifice), 0.499 mm^2 and 0.988 (oven 2, small orifice), 0.783 mm^2 and 0.991 (oven 2, medium orifice), 1.125 mm^2 and 0.992 (oven 2, large orifice), 0.497 mm^2 and 0.988 (oven 3, small orifice), 0.773 mm^2 and 0.991 (oven 3, medium orifice), and 1.150 mm^2 and 0.992 (oven 3, large orifice). For the study of 2-acetyl-5-nitrothiophene, the areas and Clausing factors of the effusion orifices, in the platinum foil of $l = 0.0125$ mm thickness, are, respectively, 0.502 mm^2 and 0.988 (oven 1, small orifice), 0.774 mm^2 and 0.991 (oven 1, medium orifice), 1.099 mm^2 and 0.992 (oven 1, large orifice), 0.509 mm^2 and 0.988 (oven 2, small orifice), 0.783 mm^2 and 0.991 (oven 2, medium orifice), 1.125 mm^2 and 0.992 (oven 2, large orifice), 0.523 mm^2 and 0.989 (oven 3, small orifice), 0.792 mm^2 and 0.991 (oven 3, medium orifice), and 1.131 mm^2 and 0.992 (oven 3, large orifice).

Results

Tables 1 and 2 list the detailed combustion results for 2-acetyl-5-nitrothiophene and 5-nitro-2-thiophenecarboxaldehyde in which $\Delta m(H_2O)$ is the deviation of the mass of water added to the calorimeter from 3965.0 g, the mass assigned to ε(calor), and ΔU_Σ is the correction to the

Table 1 Standard ($p^\circ = 0.1$ MPa) massic energy of combustion of 2-acetyl-5-nitrothiophene at $T = 298.15$ K

	1	2	3	4	5	6
m(cpd)/g	0.54521	0.82183	0.77924	0.75731	0.68977	0.78423
m'(fuse)/g	0.00294	0.00306	0.00286	0.00265	0.00307	0.00294
T_i/K	297.3017	297.2881	297.3344	297.3819	297.3905	297.3033
T_f/K	297.8960	298.1538	298.1577	298.1813	298.1232	298.1310
ΔT_ad/K	0.55450	0.83454	0.79078	0.76837	0.70011	0.79557
ε_i/J K^{-1}	74.05	74.34	74.29	74.27	74.20	74.30
ε_f/J K^{-1}	72.92	73.27	73.22	73.19	73.11	73.22
$\varepsilon_\mathrm{corr}$/J K^{-1}	20364.40	20362.31	20376.11	20367.74	20380.30	20381.13
$\Delta m(\mathrm{H_2O})$/g	−1.1	−1.6	1.7	−0.3	2.7	2.9
$-\Delta U(\mathrm{IBP})^\mathrm{a}$/J	11332.34	17054.13	16170.70	15705.93	14319.35	16272.68
ΔU(fuse)/J	47.75	49.69	46.45	43.04	49.86	47.75
$\Delta U(\mathrm{HNO_3})$/J	30.09	47.82	45.01	42.27	37.85	47.52
ΔU(ign)/J	1.11	1.10	1.10	1.10	1.11	1.10
ΔU_Σ/J	22.33	29.49	28.45	27.92	26.21	28.56
$-\Delta_\mathrm{c}u^\circ$/J g^{-1}	20601.55	20596.88	20598.01	20589.59	20594.44	20591.98
	$-\langle\Delta_\mathrm{c}u^\circ\rangle = (20595.4 \pm 1.8)$ J g^{-1}					

[a] ΔU(IBP) includes ΔU(ign)

Table 2 Standard ($p^\circ = 0.1$ MPa) massic energy of combustion of 5-nitro-2-thiophenecarboxaldehyde at $T = 298.15$ K

	1	2	3	4	5	6
m(cpd)/g	0.92610	0.83991	1.05864	1.11094	0.93373	0.97891
m'(fuse)/g	0.00299	0.00301	0.00275	0.00257	0.00260	0.00262
T_i/K	297.2584	297.4289	297.1559	297.1092	297.2816	297.2141
T_f/K	298.1324	298.2219	298.1489	298.1504	298.1637	298.1352
ΔT_ad/K	0.84537	0.76691	0.96475	1.01193	0.85006	0.89319
ε_i/J K^{-1}	74.32	74.23	74.44	74.49	74.32	74.37
ε_f/J K^{-1}	73.02	72.95	73.14	73.20	73.03	73.06
$\varepsilon_\mathrm{corr}$/J K^{-1}	20364.40	20368.16	20384.90	20382.81	20413.35	20372.77
$\Delta m(\mathrm{H_2O})$/g	−1.1	−0.2	3.8	3.3	10.6	0.9
$-\Delta U(\mathrm{IBP})^\mathrm{a}$/J	17277.26	15676.33	19737.11	20700.30	17414.68	18262.15
ΔU(fuse)/J	48.56	48.88	44.66	41.74	42.22	42.55
$\Delta U(\mathrm{HNO_3})$/J	51.64	42.92	56.12	54.80	50.86	56.60
ΔU(ign)/J	1.08	1.09	1.08	1.09	1.09	1.08
ΔU_Σ/J	30.02	28.30	32.57	33.55	30.18	31.02
$-\Delta_\mathrm{c}u^\circ$/J g^{-1}	18515.32	18521.31	18517.87	18516.04	18518.65	18522.62
	$-\langle\Delta_\mathrm{c}u^\circ\rangle = (18518.6 \pm 1.2)$ J g^{-1}					

[a] ΔU(IBP) includes ΔU(ign)

m(cpd) mass of compound burnt in each experiment, m'(fuse) mass of the fuse (cotton) used in each experiment, T_i initial temperature rise, T_f final temperature rise, ΔT_ad corrected temperature rise, ε_i energy equivalent of the contents in the initial state, ε_f energy equivalent of the contents in the final state, $\varepsilon_\mathrm{corr}$ energy equivalent of the calorimeter corrected for the deviation of mass of water added to the calorimeter, $\Delta m(\mathrm{H_2O})$ deviation of mass of water added to the calorimeter from 3965.0 g, ΔU(IBP) energy change for the isothermal combustion reaction under actual bomb conditions, ΔU(fuse) energy of combustion of the fuse (cotton), $\Delta U(\mathrm{HNO_3})$ energy correction for the nitric acid formation, ΔU(ign) electric energy for the ignition, ΔU_Σ standard state correction, $\Delta_\mathrm{c}u^\mathrm{o}$ standard massic energy of combustion

standard state. The remaining quantities are as previously described [27].

The internal energy for the isothermal bomb process, ΔU(IBP), was calculated according to Eq. 3

$$\begin{aligned}\Delta U(\mathrm{IBP}) = -\{\varepsilon(\mathrm{calor}) + c_p(\mathrm{H_2O,\ l})\Delta m(\mathrm{H_2O})\}\,\Delta T_\mathrm{ad} \\ + (T_\mathrm{i} - 298.15)\varepsilon_\mathrm{i} + (298.15 - T_\mathrm{i} - \Delta T_\mathrm{ad})e_\mathrm{f} \\ + \Delta U(\mathrm{ign}),\end{aligned} \tag{3}$$

where ΔT_{ad} is the calorimeter temperature change corrected for the heat exchange and the work of stirring.

For each compound, the products of combustion in the experiments consist of a gaseous phase and an aqueous mixture of sulphuric acid, for which the thermodynamic properties are known. The values of $\Delta_c u^o$ refer to the hypothetical combustion reactions represented by Eq. 4 for 2-acetyl-5-nitrothiophene and Eq. 5 for 5-nitro-2-thiophenecarboxaldehyde:

$$C_6H_5NO_3S(cr) + 7.25\,O_2(g) + 113.5\,H_2O\,(l) \rightarrow 6CO_2(g) + 0.5N_2 + H_2SO_4 \cdot 115\,H_2O(l) \quad (4)$$

$$C_5H_3NO_3S(cr) + 5.75O_2(g) + 114.5H_2O(l) \rightarrow 5CO_2(g) + 0.5N_2 + H_2SO_4 \cdot 115\,H_2O(l) \quad (5)$$

Tables 1 and 2 list also the mean value, $\langle \Delta_c u^o \rangle$, and its standard deviation, respectively, for 2-acetyl-5-nitrothiophene and 5-nitro-2-thiophenecarboxaldehyde.

The derived standard molar values for the energies, $\Delta_c U^o_m$(cr), and enthalpies,$\Delta_c H^o_m$ (cr), of the combustion reactions (4) and (5), as well as the standard molar enthalpies of formation of both studied compounds, in the crystalline phase, $\Delta_f H^o_m$(cr), at T = 298.15 K, are given in Table 3.

The uncertainties of the standard molar energies and enthalpies of combustion are twice the overall standard deviation of the mean and include the uncertainties in calibration and in the values of auxiliary quantities used [31, 32].

Table 3 Derived standard (p^o = 0.1 MPa) molar energies of combustion, $\Delta_c U^o_m$, standard molar enthalpies of combustion, $\Delta_c H^o_m$, and standard molar enthalpies of formation, $\Delta_f H^o_m$, for the crystalline compounds, at T = 298.15 K

Compound	$-\Delta_c U^o_m$ (cr)/kJ mol^{-1}	$-\Delta_c H^o_m$ (cr)/kJ mol^{-1}	$-\Delta_f H^o_m$ (cr)/kJ mol^{-1}
2-Acetyl-5-nitrothiophene	3525.4 ± 1.3	3527.3 ± 1.3	150.3 ± 1.5
5-Nitro-2-thiophenecarboxaldehyde	2910.1 ± 1.0	2910.7 ± 1.0	87.6 ± 1.2

Table 4 Knudsen effusion results for the two nitrothiophene derivatives

T/K	t/s	Orifices	p/Pa			$10^2 \cdot \Delta\ln(p/Pa)$		
			Small	Medium	Large	Small	Medium	Large
2-Acetyl-5-nitrothiophene								
308.13	23561	A1-B4-C7	0.071	0.070	0.071	0.9	0.2	1.1
310.16	23561	A2-B5-C8	0.087	0.089	0.088	−3.7	−1.2	−2.3
312.21	23561	A3-B6-C9	0.118	0.115	0.115	1.2	−1.1	−1.7
314.10	19935	A1-B4-C7	0.155	0.149	0.148	5.0	1.0	0.2
316.10	19935	A2-B5-C8	0.195	0.191	0.186	3.5	1.7	−0.9
318.21	19935	A3-B6-C9	0.246	0.241	0.234	1.9	−0.3	−3.1
320.11	17097	A1-B4-C7	0.309	0.304	0.302	2.1	0.3	−0.4
322.10	17097	A2-B5-C8	0.385	0.382	0.374	−0.3	−1.3	−3.3
324.22	17097	A3-B6-C9	0.498	0.478	0.493	0.9	−3.1	−0.1
326.12	10074	A1-B4-C7	0.622	0.614	0.608	2.4	1.0	0.0
328.14	10074	A2-B5-C8	0.779	0.764	0.752	2.1	0.2	−1.4
330.20	10074	A3-B6-C9	0.988	0.956	0.923	2.9	−0.5	−3.9
5-Nitro-2-thiophenecarboxaldehyde								
299.13	15651	A3-B6-C9	0.185	0.184	0.186	1.2	0.7	1.7
301.28	15651	A2-B5-C8	0.232	0.229	0.227	0.0	−1.5	−2.3
303.13	15651	A1-B4-C7	0.289	0.287	0.286	−0.4	−1.2	−1.4
305.30	10825	A3-B6-C9	0.388	0.381	0.375	3.2	1.4	−0.1
307.27	10825	A2-B5-C8	0.486	0.474	0.460	2.6	0.2	−2.7
309.13	10825	A1-B4-C7	0.579	0.584	0.583	−1.5	−0.6	−0.8
311.31	7212	A3-B6-C9	0.752	0.766	0.739	−0.2	1.6	−1.9
313.23	7212	A2-B5-C8	0.953	0.939	0.924	1.8	0.3	−1.3
315.11	7212	A1-B4-C7	1.184	1.155	1.134	2.6	0.1	−1.8

The values of $\Delta_f H_m^o(\mathrm{cr})$, at $T = 298.15$ K, of the two nitrothiophene derivatives studied, were derived from the respective $\Delta_c H_m^o(\mathrm{cr})$, using the values of the standard molar enthalpies of formation of H_2SO_4 in $115H_2O$(l), −(887.81 ± 0.01) kJ mol^{-1} [25], H_2O (l), −(285.830 ± 0.042) kJ mol^{-1}[33] and CO_2 (g), −(393.51 ± 0.13) kJ mol^{-1} [33].

The integrated form of the Clausius–Clapeyron equation, ln(p/Pa) = a – b (T/K)$^{-1}$, where a is a constant and $b = \Delta_{cr}^{g} H_m^o(\langle T \rangle)/R$, was used to derive the standard molar enthalpies of sublimation at the mean temperature of the experimental temperature range. The experimental results obtained from each effusion cell, together with the residuals of the Clausius–Clapeyron equation, derived from least squares adjustments, are presented in Table 4.

For each compound, the calculated enthalpies of sublimation obtained from each individual hole are in agreement within experimental error. The entropies of sublimation, at equilibrium conditions, were calculated as

$$\Delta_{cr}^{g} S_m(\langle T \rangle, p(\langle T \rangle)) = \Delta_{cr}^{g} H_m^o(\langle T \rangle)/\langle T \rangle \qquad (6)$$

Table 5 presents for each hole used and for the global treatment of all the (p,T) points obtained for each studied compound, the detailed parameters of the Clausius–Clapeyron equation, together with the calculated standard deviations and the standard molar enthalpies of sublimation at the mean temperature of the experiments $T = \langle T \rangle$. The equilibrium pressure at this temperature $p(\langle T \rangle)$ and the entropies of sublimation, at equilibrium conditions, are also presented. The plots of ln $p = f$ (1/T) for the global results of the two compounds experimentally studied are presented in Fig. 2. Table 6 lists the (p,T) values calculated from the (p,T) equations for the crystalline compounds, within the experimental range of pressures used: 0.1–1.0 Pa. Sublimation enthalpies, at $T = 298.15$ K, were derived from the sublimation enthalpies calculated at the mean temperature $\langle T \rangle$ of the experiments, by the equation

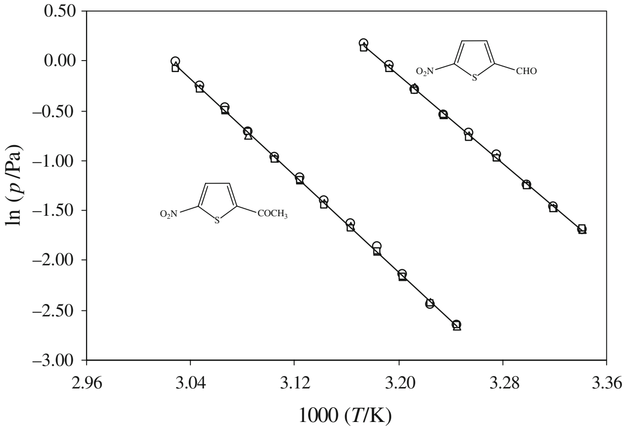

Fig. 2 Plots of ln (p/Pa) against 1/T for 2-acetyl-5-nitrothiophene and 5-nitro-2-thiophenecarboxaldehyde: *open circle* small holes; *open triangle* medium holes; *open square* large holes

$$\Delta_{cr}^{g} H_m^o(T = 298.15\,K) = \Delta_{cr}^{g} H_m^o(\langle T \rangle) + \Delta_{cr}^{g} C_{p,m}^o(298.15 - \langle T \rangle) \qquad (7)$$

For each compound studied, the value $\Delta_{cr}^{g} C_{p,m}^o = -50$ J K^{-1} mol^{-1} was assumed in accordance with similar estimations made by other authors [34], which we have already used in previous papers for other organic compounds [10, 15, 16, 35–49].

Table 7 presents, for each compound, the values, at $T = 298.15$ K, of the standard molar enthalpies, entropies, and Gibbs energies of sublimation.

For the two compounds experimentally studied, the standard molar enthalpies of formation in the gaseous state, at $T = 298.15$ K, were derived from the calculated standard molar enthalpies of formation in the crystalline state and, the standard molar enthalpies of sublimation, given in Tables 3 and 7, respectively, and are presented in Table 8.

Table 5 Experimental results for 2-acetyl-5-nitrothiophene and 5-nitro-2-thiophenecarboxaldehyde where a and b are from Clausius–Clapeyron equation, ln (p/Pa) = a − b (K/T) and $b = \Delta_{cr}^{g} H_m^o(\langle T \rangle)/R$; $R = 8.314472$ J K^{-1} mol^{-1}

Orifices	a	b	$\langle T \rangle$/K	$p(\langle T \rangle)$/Pa	$\Delta_{cr}^{g} H_m^o(\langle T \rangle)$/kJ mol^{-1}	$\Delta_{cr}^{g} S_m(\langle T \rangle, p(\langle T \rangle))$/J K^{-1} mol^{-1}
2-Acetyl-5-nitrothiophene						
A1-A2-A3	36.85 ± 0.29	12171 ± 92			101.2 ± 0.8	
B4-B5-B6	36.49 ± 0.18	12064 ± 57			100.3 ± 0.5	
C7-C8-C9	36.30 ± 0.21	12008 ± 67			99.8 ± 0.6	
Global results	36.55 ± 0.16	12081 ± 37	319.17	0.271	100.4 ± 0.4	314.7 ± 1.3
5-Nitro-2-thiophenecarboxaldehyde						
A1-A2-A3	35.24 ± 0.34	11055 ± 106			91.9 ± 0.9	
B4-B5-B6	35.24 ± 0.22	11059 ± 66			92.0 ± 0.6	
C7-C8-C9	34.73 ± 0.26	10905 ± 79			90.7 ± 0.6	
Global results	35.07 ± 0.19	11007 ± 58	307.21	0.470	91.5 ± 0.5	297.9 ± 1.6

Table 6 Calculated (p,T) values from the vapour pressure equations for the studied compounds

p/Pa	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	T/K									
2-Acetyl-5-nitrothiophene	311.0	316.6	320.0	322.5	324.4	326.0	327.4	328.6	329.6	330.6
5-Nitro-2-thiophenecarboxaldehyde	294.5	300.1	303.4	305.8	307.7	309.3	310.7	311.8	312.9	313.8

Table 7 Values of the standard (p^{o} = 0.1 MPa) molar enthalpies, $\Delta_{\mathrm{cr}}^{\mathrm{g}}H_{\mathrm{m}}^{\mathrm{o}}$, entropies, $\Delta_{\mathrm{cr}}^{\mathrm{g}}S_{\mathrm{m}}^{\mathrm{o}}$, and Gibbs energies $\Delta_{\mathrm{cr}}^{\mathrm{g}}G_{\mathrm{m}}^{\mathrm{o}}$, of sublimation, at T = 298.15 K, for the studied compounds

Compound	$\Delta_{\mathrm{cr}}^{\mathrm{g}}H_{\mathrm{m}}^{\mathrm{o}}$/ kJ mol^{-1}	$\Delta_{\mathrm{cr}}^{\mathrm{g}}S_{\mathrm{m}}^{\mathrm{o}}$/ J K^{-1} mol^{-1}	$\Delta_{\mathrm{cr}}^{\mathrm{g}}G_{\mathrm{m}}^{\mathrm{o}}$/ kJ mol^{-1}
2-Acetyl-5-nitrothiophene	101.5 ± 0.4	211.5 ± 1.3	38.4 ± 0.6
5-Nitro-2-thiophene carboxaldehyde	92.0 ± 0.5	197.4 ± 1.6	33.1 ± 0.7

Table 8 Standard (p^{o} = 0.1 MPa) molar enthalpies of formation, in both crystalline and gaseous phases, and standard molar enthalpies of sublimation, at T = 298.15 K

Compound	$-\Delta_{\mathrm{f}}H_{\mathrm{m}}^{\mathrm{o}}$ (cr)/ kJ mol^{-1}	$\Delta_{\mathrm{cr}}^{\mathrm{g}}H_{\mathrm{m}}^{\mathrm{o}}$/ kJ mol^{-1}	$\Delta_{\mathrm{f}}H_{\mathrm{m}}^{\mathrm{o}}$ (g)/ kJ mol^{-1}
2-Acetyl-5-nitrothiophene	150.3 ± 1.5	101.5 ± 0.4	−48.8 ± 1.6
5-Nitro-2-thiophene carboxaldehyde	87.6 ± 1.2	92.0 ± 0.5	4.4 ± 1.3

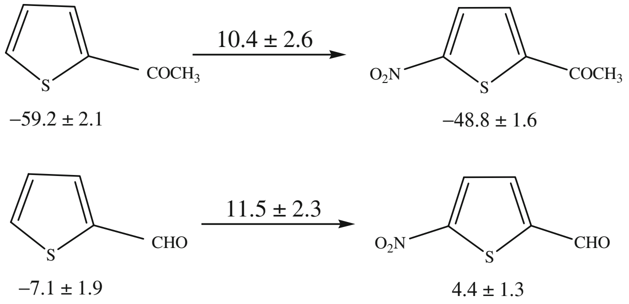

Fig. 3 Enthalpic increment of the entrance of a –NO$_2$ group in the 5th position of 2-acetyl-5-nitrothiophene and of 5-nitro-2-thiophenecarboxaldehyde

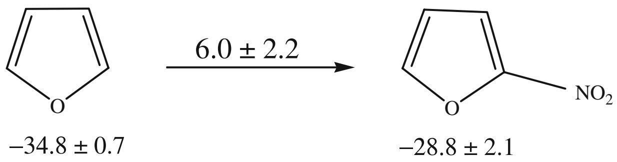

Fig. 4 Enthalpic increment to the formation of 2-nitrofuran

Discussion

The energetic influence of the nitro group in the thiophene ring had to be evaluated through other thiophene derivatives that also have this substituent group since the available samples of the 2-nitrothiophene have a low purity (mass fraction purity of 0.85), being the major contaminant the 3-nitrothiophene isomer and it was not possible, so far, the separation of the two isomers in the extension needed to obtained a sample of high purity. Thus, the enthalpic increment for the introduction of a nitro group in the position 5 of thiophene ring was calculated from the literature values of the standard molar enthalpies of formation, in the gaseous phase, of 2-acetylthiophene, $\Delta_{\mathrm{f}}H_{\mathrm{m}}^{\mathrm{o}}(\mathrm{C_6H_6OS, g}) = -59.2 \pm 2.1$ kJ mol^{-1} [9], 2-thiophenecarboxaldehyde $\Delta_{\mathrm{f}}H_{\mathrm{m}}^{\mathrm{o}}(\mathrm{C_5H_4OS, g}) = -7.1 \pm 1.9$ kJ mol^{-1} [12], and the values reported in this article, as shown in the scheme of Fig. 3.

As shown in the Fig. 3, the calculated enthalpic increments of the entrance of a nitro group in the 5th position of the thiophene derivatives presented above are in excellent agreement, which may be indicative of the energetic effect caused by the introduction of this group in a *ortho* position of the thiophene ring. The addition of a nitro group to the furan ring yields an enthalpic increment of (6.0 ± 2.2) kJ mol^{-1}, as shown in the scheme of Fig. 4, calculated from the standard molar enthalpies of formation in the gaseous phase of furan, −(34.8 ± 0.7) kJ mol^{-1} [50] and of 2-nitrofuran, −(28.8 ± 2.1) kJ mol^{-1} [50] being slightly lower, within the associated uncertainties, to the enthalpic increments calculated above for the entrance of a –NO$_2$ group in the 5th position of the thiophene derivatives presented.

It is worth noting that the introduction of a nitro group in the aromatic rings presented above has a destabilizing effect, because this group is an electron acceptor by inductive and resonance effects and removes electronic density from the ring.

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References

1. Wang CY, Muraoka K, Bryan GT. Mutagenicity of nitrofurans, nitrothiophenes, nitropyrroles, nitroimidazole, aminothiophenes, and aminothiazoles in salmonella typhimurium. Cancer Res. 1975;35:3611–7.
2. http://www.patentstorm.us/patents/6262055/description.html. Accessed 03 Dec 2008.
3. http://www.wipo.int/pctdb/en/wo.jsp?wo=2007033080&IA=US2006035316&DISPLAY=DESC. Accessed 03 Dec 2008.
4. Thomson P, Naylor MA, Everett SA, Stratford MRL, Lewis G, Hill S, et al. Synthesis and biological properties of bioreductively targeted nitrothienyl prodrugs of combretastatin A-4. Mol Cancer Ther. 2006;5:2886–94.
5. Rudra S, Yadav A, Rao AVSR, Srinivas ASSV, Pandya M, Bhateja P, et al. Synthesis and antibacterial activity of potent heterocyclic oxazolidinones and the identification of RBx 8700. Bioorgan Med Chem Lett. 2007;17:6714–9.
6. McBurney B, Crundwell G, Updegraff JB III, Zeller M, Hunter AD. 5-Nitrothiophene-2-carbaldehyde. Acta Crystallogr E. 2005;61:o1221–2.
7. Ribeiro da Silva MAV, Santos AFLOM. Thermochemical study of 2- and 3-alkyl substituted thiophenes. J Therm Anal Calorim. 2007;88:7–17.
8. Roux MV, Temprado M, Notário R, Chickos JS, Santos AFLOM, Ribeiro da Silva MAV. Experimental and computational thermochemical study of 2- and 3-thiopheneacetic acid methyl esters. J Phys Chem A. 2007;111:5280–6.
9. Roux MV, Temprado M, Jiménez P, Notário R, Chickos JS, Santos AFLOM, et al. Thermochemistry of 2- and 3-acetylthiophenes: calorimetric and computational study. J Phys Chem A. 2007;111:11084–92.
10. Ribeiro da Silva MAV, Santos AFLOM. Standard molar enthalpies of formation and of sublimation of 2-thiophenecarboxamide and 2-thiopheneacetamide. J Chem Thermodyn. 2008;40:166–73.
11. Ribeiro da Silva MAV, Santos AFLOM. Thermochemistry of substituted thiophenecarbonitrile derivatives. J Chem Thermodyn. 2008;40:225–31.
12. Ribeiro da Silva MAV, Santos AFLOM. Energetics of thiophenecarboxaldehydes and some of its alkyl derivatives. J Chem Thermodyn. 2008;40:917–23.
13. Ribeiro da Silva MAV, Santos AFLOM. Experimental study on the thermochemistry of 2, 5-dimethylthiophene and its acetyl derivative. J Chem Thermodyn. 2008;40:1217–21.
14. Ribeiro da Silva MAV, Santos AFLOM. Experimental thermochemical study of the three methyl substituted 2-acetylthiophene isomers. J Chem Thermodyn. 2008;40:1309–13.
15. Ribeiro da Silva MAV, Santos AFLOM. Thermochemical properties of three 2-thiophenecarboxylic acid derivatives. J Chem Thermodyn. 2008;40:1451–7.
16. Ribeiro da Silva MAV, Santos AFLOM. Thermochemical and thermophysical study of 2-thiophenecarboxylic acid hydrazide and 2-furancarboxylic acid hydrazide. J Chem Thermodyn. 2008;40:1588–93.
17. Ribeiro da Silva MAV, Santos AFLOM. Energetics of some sulphur heterocycles. J Therm Anal Calorim A. 2009;95:333–44.
18. Cox JD, Gundry HA, Head A. Thermodynamic properties of fluorine compounds. Part 1. Heats of combustion of *p*-fluorobenzoic acid, pentafluorobenzoic acid, hexafluorobenzene and decafluorocyclohexene. Trans Faraday Soc. 1964;60:653–65.
19. Gundry HA, Head A. Thermodynamic properties of aliphatic halogen compounds 4. The enthalpy of combustion of 1,1,1,2-tetrachloroethane. J Chem Thermodyn. 1978;10:195–200.
20. Good WD, Scott DW, Waddington G. Combustion calorimetry of organic fluorine compounds by a rotating-bomb method. J Phys Chem. 1956;60:1080–9.
21. Santos LMNBF. Estudo termoquímico de algumas β-dicetonas, monotio- β-dicetonas e respectivos complexos metálicos. PhD Thesis. University of Porto; 1995.
22. Coops J, Jessup RS, van Nes K. Calibration of calorimeters for reactions in a bomb at constant volume. In: Rossini FD, editor. Experimental thermochemistry, vol. 1. New York: Interscience; 1956.
23. Waddington G, Sunner S, Hubbard WN. Combustion in a bomb of organic sulfur compounds. In: Rossini FD, editor. Experimental thermochemistry, vol. 1. New York: Interscience; 1956.
24. Vogel AI. Quantitative inorganic analysis. London: Longman; 1978.
25. Wagman DD, Evans WH, Parker VB, Shum RH, Halow F, Bailey SM, Churney KL, Nuttall RL. NBS tables of chemical thermodynamic properties. J Phys Chem Ref Data. 1982;11(Suppl 2).
26. Washburn EW. Standard states for bomb calorimetry. J Res Nat Bur Stand. 1933;10:525–58.
27. Hubbard WN, Scott DW, Waddington G. Standard states and corrections for combustions in a bomb at constant volume. In: Rossini FD, editor. Experimental thermochemistry, vol. 1. New York: Interscience; 1956.
28. Good WD, Scott DW. Combustion in a bomb of organic fluorine compounds. In: Skinner HA, editor. Experimental thermochemistry, vol. 2. New York: Interscience; 1962.
29. Wieser ME. Atomic weights of the elements 2005 (IUPAC Technical Report). Pure Appl Chem. 2006;78:2051–66.
30. Ribeiro da Silva MAV, Monte MJ, Santos LMNBF. The design, construction, and testing of a new Knudsen effusion apparatus. J Chem Thermodyn. 2006;38:778–87.
31. Rossini FD. Assignment of uncertainties to thermochemical data. In: Rossini FD, editor. Experimental thermochemistry, vol 1. New York: Interscience; 1956.
32. Olofsson G. Assigment of uncertainties. In: Sunner S, Månsson M, editors. Combustion calorimetry. Oxford: Pergamon; 1979.
33. Cox JD, Wagman DD, Medvedev VA. CODATA key values for thermodynamics. New York: Hemisphere; 1989.
34. Burkinshaw PM, Mortimer CT. Enthalpies of sublimation of transition metal complexes. JCS Dalton Trans. 1984;75–77.
35. Ribeiro da Silva MAV, Monte MJS, Matos MAR. Enthalpies of combustion, vapour pressures, and enthalpies of sublimation of 8-hydroxyquinoline, 5-nitro-8-hydroxyquinoline, and 2-methyl-8-hydroxyquinoline. J Chem Thermodyn. 1989;21:159–66.
36. Ribeiro da Silva MAV, Matos MAR, Monte MJS. Enthalpies of combustion, vapour pressures, and enthalpies of sublimation of 2-hydroxyquinoline, 4-methyl-2-hydroxyquinoline, 4-hydroxyquinoline, and 2-methyl-4-hydroxyquinoline. J Chem Thermodyn. 1990;22:609–16.
37. Ribeiro da Silva MAV, Monte MJS. Vapour pressures and enthalpies of sublimation of six halogen-substituted 8-hydroxyquinolines. J Chem Thermodyn. 1992;24:715–24.
38. Ribeiro da Silva MAV, Matos MAR, Monte MJS, Alves MCB, Vieira JMAP. Enthalpies of combustion, vapour pressures, and enthalpies of sublimation of 3-, 5-, 6-, and 8-aminoquinoline. J Chem Thermodyn. 1993;25:579–90.
39. Ribeiro da Silva MAV, Monte MJS. Vapour pressures and standard molar enthalpies of sublimation of four crystalline β-diketones. J Chem Thermodyn. 1992;24:1219–28.
40. Ribeiro da Silva MAV, Matos MAR, Amaral LMPF. Enthalpies of combustion, vapour pressures, and enthalpies of sublimation of 2-cyanoquinoline and 3-cyanoquinoline. J Chem Thermodyn. 1995;27:1187–96.

41. Ribeiro da Silva MAV, Matos MAR, Amaral LMPF. Enthalpies of combustion, vapour pressures, and enthalpies of sublimation of 2-phenylquinoline and 2, 2′-biquinoline. J Chem Thermodyn. 1997;29:1129–36.
42. Ribeiro da Silva MAV, Carvalho APSMC, Monte MJS, Giera E. Enthalpies of combustion, vapour pressures, and enthalpies of sublimation of 5-amino-6-nitroquinoline and 4-aminoquinaldine. J Chem Thermodyn. 1998;30:815–23.
43. Ribeiro da Silva MAV, Amaral LMPF, Matos MA. Enthalpies of combustion, vapour pressures, and enthalpies of sublimation of 5-, 6-, and 8-nitroquinoline and 8-nitroquinaldine. J Chem Thermodyn. 1997;29:295–303.
44. Ribeiro da Silva MAV, Monte MJS, Ribeiro JR. Vapour pressures and the enthalpies and entropies of sublimation of five dicarboxylic acids. J Chem Thermodyn. 1999;31:1093–107.
45. Ribeiro da Silva MAV, Lima LMSS, Amaral LMPF, Ferreira AIMCL, Gomes JRB. Standard molar enthalpies of formation, vapour pressures, and enthalpies of sublimation of 2-chloro-4-nitroaniline and 2-chloro-5-nitroaniline. J Chem Thermodyn. 2003;35:1343–59.
46. Ribeiro da Silva MAV, Amaral LMPF, Santos AFLOM, Gomes JRB. Thermochemistry of some alkylsubstituted anthracenes. J Chem Thermodyn. 2006;38:367–75.
47. Ribeiro da Silva MAV, Amaral LMPF, Santos AFLOM, Gomes JRB. Thermochemistry of nitronaphthalenes and nitroanthracenes. J Chem Thermodyn. 2006;38:748–55.
48. Ribeiro da Silva MAV, Amaral LMPF, Gomes JRB. Experimental and computational studies on the molecular energetics of chlorobenzophenones. J Phys Chem B. 2007;111:13033–40.
49. Ribeiro da Silva MAV, Amaral LMPF. Standard molar enthalpies of formation of some vinylfuran derivatives. J Chem Thermodyn. 2009;41:349–54.
50. Pedley JB. Thermochemical data and structures of organic compounds. College Station: Thermodynamics Research Center, CRC Press; 1994.