

Melting Point and Normal Boiling Point Correlations: Applications to Rigid Aromatic Compounds

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Simple group contribution approaches have been developed to estimate the boiling point and melting point of rigid organic molecules based on their chemical structures. The boiling point estimation requires only additive constitutive properties, whereas melting point prediction employs additive constitutive properties and symmetry. The effects of intramolecular hydrogen bonding and the presence of ortho substituents in biphenyls on the boiling and melting temperatures are discussed.

INTRODUCTION

At least one of the phase transition temperatures (boiling point and melting point) is known for almost every organic compound. Despite this, there are very few useful means for quantitatively relating these properties to chemical structures.

Various methods in boiling point prediction have been summarized by Rechsteiner.¹ The relationships between boiling point and several molecular parameters such as polarizability, dipolarity,² and topological descriptors^{3,4} for certain classes of compounds have been investigated. Homologous series have been studied by Screttas et al.⁵ Stanton et al. have predicted the normal boiling points of heterocyclic compounds.^{6,7}

Very few methods have been proposed for melting point predictions. As early as 1879, the trend of increasing melting point for more symmetrical and more compact molecules⁸⁻¹⁰ and for homologous series with higher molecular weight¹¹ has been observed.

A quantitative structure activity relationship (QSAR) approach has been employed in melting point prediction of substituted anilines.^{12,13} Joback and Reid proposed a group contribution approach for estimating several physical properties of pure materials,¹⁴ including melting point and boiling point. Tsakanikas and Yalkowsky have developed an empirical equation which employs the additive constitutive properties together with molecular flexibility and rotational symmetry for predicting the melting points of aliphatic hydrocarbons.¹⁵

Abramowitz and Yalkowsky have also studied the relationship between boiling point and melting point of non-hydrogen bonding substituted benzenes.¹⁶ They also have developed an approach to estimate the melting point of PCB congeners by using the number of chlorine atoms and several geometric factors which in turn can be applied to predict the solubilities of the PCB's.¹⁷

Recently Simamora and Yalkowsky¹⁸ proposed simple approaches for predicting the boiling points and melting points of non-hydrogen bonding rigid aromatics. It has been shown that boiling point estimation requires only additive constitutive properties, whereas melting point prediction employs additive constitutive properties and a non-additive non-constitutive property, rotational symmetry.

In this study, the applicability of the previous method¹⁸ is expanded to include compounds that contain a single hydrogen bonding group in addition to the non-hydrogen bonding groups used in that study.

The enthalpy of boiling, ΔH_b , and enthalpy of melting, ΔH_m , are estimated from group contributions. The summation

of the group values represents the total enthalpies of transition of each compound. Transition temperatures are calculated by dividing the enthalpies of transition above by the corresponding entropy terms.

THEORETICAL BACKGROUND

At the phase transition temperature, the free energy of transition is equal to zero. Therefore, the phase transition temperature can be related to the enthalpy, ΔH_{tr} , and entropy of transition, ΔS_{tr} .

$$T_{tr} = \Delta H_{tr} / \Delta S_{tr} \quad (1)$$

The entropy of boiling for rigid aromatics is assumed to be equal to a constant proposed by Trouton, 21 cal/mol.¹⁹ The entropy of melting is calculated by using an equation proposed by Dannenfelser et al.²⁰ that employs the rotational symmetry, σ , which is defined as the number of ways that a molecule can rotate to give indistinguishable images.

$$\Delta S_b = 21 \text{ cal}/(\text{deg mol}) \quad (2)$$

$$\Delta S_m = 13.5 - R \ln \sigma \quad \text{cal}/(\text{deg mol}) \quad (3)$$

where R is the gas constant. Therefore, the boiling point, T_b , and the melting point, T_m , are given by

$$T_b = \frac{\Delta H_b}{21} \quad (4)$$

$$T_m = \frac{\Delta H_m}{13.5 - 4.6 \log \sigma} \quad (5)$$

Thus, the melting point of a compound can be estimated from the symmetry and the enthalpy of melting, whereas the boiling point can be predicted simply from the enthalpy of boiling.

EXPERIMENTAL SECTION

The data used in this study were collected from several sources.^{21,22} The data sets for boiling point (at atmospheric pressure) and melting point correlations consist of 246 and 1186 aromatics, respectively. Rigid benzenoids or heterocyclics with one or two directly linked cyclic systems, i.e., diphenylmethane derivatives, were excluded. The compounds employed in this study include monocyclic and polycyclic rigid aromatics containing a single hydrogen bonding group, i.e., hydroxy, aldehyde, primary amine, carboxylic, or amide, as well as the non-hydrogen bonding groups that were used in

Table I. Compounds That Are Employed in the Data Sets

compound	T_m	T_b
non-hydrogen bonding aromatics	525	111
aromatic hydroxyl containing compounds	150	30
aromatic carboxyl containing compounds	121	2
aromatic amino containing compounds	144	43
aromatic amide containing compounds	12	3
aromatic aldehyde containing compounds	28	11
aromatic ring nitrogen containing compounds	201	41
total	1181	241

Table II. Description and Designation of the Molecular Descriptors

description	designation
N-AR	aromatic nitrogen
C-AR	aromatic carbon
CH-AR	aromatic C-H
C-BIP	C-AR involved in biphenyl linkage
Y-F	fluorine atom attached to sp^2 carbon
Y-Cl	chlorine atom attached to sp^2 carbon
Y-Br	bromine atom attached to sp^2 carbon
Y-I	iodine atom attached to sp^2 carbon
Y-CH ₃	methyl group attached to sp^2 carbon
Y-CH ₂ ^a	methylene group attached to sp^2 carbon
Y-CN	cyano group attached to sp^2 carbon
Y-NO ₂	nitro group attached to sp^2 carbon
Y-OH	hydroxy group attached to sp^2 carbon
Y-CHO	aldehyde group attached to sp^2 carbon
Y-COOH	carboxy group attached to sp^2 carbon
Y-NH ₂	amino group attached to sp^2 carbon
Y-CONH ₂	amide group attached to sp^2 carbon
IHB-4	four membered ring intra-HB
IHB-5	five membered ring intra-HB
IHB-6	six membered ring intra-HB
IHB-7	seven membered ring intra-HB
O-BIP	substituent present in biphenyl at the 2,2',6, and/or 6' positions

^a In acenaphthene, etc.Table III. Regression Analysis for Normal Boiling Point (T_b) and Melting Point (T_m)

equation	n	r^2	s
1. $T_b = \sum n_i b_i / 21$	241	0.9994	13.66
2. $T_m = \sum n_i m_i / (13.5 - 4.6 \log \sigma)$	1181	0.9910	36.63

a previous study¹⁸ (i.e., fluorine, chlorine, bromine, iodine, methyl, cyano, and nitro groups). No ketones, esters, or secondary or tertiary sp^3 -amino functions were considered. The number of compounds in each group are listed in Table I.

Statistical Analysis. dBase III software was used to develop the data base for all the compounds used in this study on an IBM PC compatible computer. The statistical analysis was performed using multiple regression programs in SAS.²³ The r^2 values were used as a measure of correlation for the equations tested. The T values were used to measure the significance of each independent variable (group value) toward the equation developed.

Additive Constitutive Descriptors. The description and designation of the additive constitutive descriptors, i.e., molecular fragments for normal boiling point and melting point correlations employed in this study, follow the designations previously described.¹⁸

Correction Factors. In addition to the additive constitutive descriptors, two non-constitutive descriptors (correction factors) are designed as follows:

Intramolecular Hydrogen Bonding Parameters. Intramolecular hydrogen bonding parameters, IHB, are designed to account for the fact that compounds with intramolecular

hydrogen bonding have lower T_b and T_m compared to their isomers which do not form intramolecular hydrogen bonding.

IHB is employed for compounds that contain hydrogen acceptor(s) such as halogens, aromatic nitrogen, and NO₂ which are adjacent (ortho) to the hydrogen bonding groups. The IHB parameters reflect the size of the ring formed by intramolecular hydrogen bonding. They are described as follows:

- IHB-4 - aromatic nitrogen of, e.g., pyridine ortho to hydroxy or primary amine
- IHB-5 - halogens ortho to hydroxyl or primary amine
- aromatic nitrogen ortho to carboxyl or amide group
- hydroxyl or primary amine group at the 8 position of quinoline
- IHB-6 - halogens ortho to carboxyl or amide group
- hydroxyl or primary amine at the 1 position and halogens at the 8 position of naphthalene
- carboxyl or amide group at the 8 position of quinoline
- IHB-7 - nitro group ortho to carboxyl or amide group
- halogens at the 1 position and carboxyl or amide group at the 8 position of naphthalene
- nitro group at the 1 position and hydroxyl or primary amine at the 8 position of naphthalene

Biphenyl Parameter (O-BIP). The presence of substituent(s) at the 2, 2', 6, and/or 6' positions of biphenyl was shown to alter the dihedral angles between the two phenyl rings.²⁴ Biphenyls that possess one substituent at one of the positions above is said to have O-BIP = 1 and biphenyl with two substituents has O-BIP = 2, etc. Table II summarizes the description and the designation of the molecular descriptors (molecular fragments and correction factors).

It is assumed that the enthalpies of boiling and melting are equal to the sum of the contribution of the molecular descriptors:

$$\Delta H_b = \sum n_i b_i \quad (6)$$

$$\Delta H_m = \sum n_i m_i \quad (7)$$

where n_i is the number of occurrences of molecular descriptor i in the compound, b_i is the contribution of molecular descriptor i to the heat of boiling, and m_i is the contribution of molecular descriptor i to the heat of melting.

RESULTS

Table III shows the results of regression analysis for the boiling point and melting point estimations. The T tests show that all of the molecular descriptors except the aromatic carbon of the melting point prediction and the IHB-6, IHB-7, and O-BIP of boiling point estimation are significant. The insignificance of IHB-6 and IHB-7 might be due to the fact that they are not likely to form in the liquid state. O-BIP is not significant in the boiling point regression since the effect of the planarity on the boiling point is small. However, it does

Table IV. Group Values and Correction Factors for the Heat of Transition (cal/mol)

group values	b_i	m_i	group values	b_i	m_i
C-AR	-144	64 ^a	Y-CN	3194	1380
CH-AR	1332	445	Y-OH	2830	1708
C-BIP	-1164	-368	Y-NH ₂	3182	1594
N-AR	1538	1034	Y-CONH ₂	4610	3088
Y-F	1393	410	Y-COOH	4277	2968
Y-Cl	2210	763	Y-CHO	2737	1339
Y-Br	2595	894	IHB-4	1443	696
Y-I	3286	1021	IHB-5	-407	-303
Y-CH ₃	1902	576	IHB-6	42 ^a	-400
Y-CH ₂	2102	555	IHB-7	-610 ^a	-527
Y-NO ₂	3349	1161	O-BIP	-352 ^a	-353

^a Not significant.

affect the melting point significantly. The results are summarized in Table IV.

The group contribution values which represent the enthalpy of vaporization, b_i , and enthalpy of melting, m_i , together with the correction factors obtained from the regressions are listed in Table IV. It can be seen from Table IV that the group values of b_i and m_i increase as the molecular size and the polarity increase. In the halogen series, iodine has the highest group values and fluorine has the lowest.

The hydrogen bonding groups tend to have higher b_i and m_i than the non-hydrogen bonding groups due to their ability to form intermolecular hydrogen bonding. Carboxyl and amide groups have the highest b_i and m_i values.

The five, six, and seven membered ring intramolecular hydrogen bonding parameters give negative values, or, in other words, they appear to reduce the transition temperatures. However, interestingly, IHB-4 gives a positive value in both boiling point and melting point equations, and IHB-6 has a non-significant positive value which is close to zero in the boiling point equation.

DISCUSSION

It can be seen from Table III that the boiling point correlation gives a reliable result by using a simple group contribution of the enthalpy of vaporization and the correction factors either for isomer or non-isomer organic molecules. We should point out that organic isomers have relatively close boiling points. The ability of this method to predict the boiling points quite well is due to the fact that boiling point is mainly affected by the enthalpy of vaporization (eq 4). It is known that the enthalpy of vaporization is the energy input required to dissociate liquid into free molecules.

We also studied the effect of the correction factors on boiling point by using the additive constitutive properties (molecular fragments) alone in the regression (i.e., the IHB's and O-BIP parameters were not used). They give a standard deviation of 17.47 K and $r^2 = 0.9989$. It can be seen that the addition of five correction factors in the boiling point equation decreases the standard deviation by only about 4 K, but overall the regression using molecular fragments alone is quite good. Therefore, it can be concluded that in rigid polyfunctional aromatics the effect of a single hydrogen bonding group and the presence of ortho substituents in biphenyls are roughly additive. Unlike boiling point, organic isomers have significantly different melting points, e.g., para isomers always have higher melting points than their meta and ortho isomers. In general, the more symmetrical a molecule, the higher the melting point. This trend has been observed in the end of nineteenth century by Carnelley⁸ and Beacall.⁹ They concluded that the more symmetrical the organic molecule, the

greater is the resistance which it offers to the passage from the solid to the liquid state.^{8,9} However, these observations were not quantitative.

The melting point of an organic molecule is controlled primarily by two factors, namely, the intermolecular forces between molecules (such as van der Waals interaction, dipolar forces, hydrogen bonds) and the symmetry of the molecules which determines how likely they are to pack in the crystal lattice. The affect of intramolecular hydrogen bonding on melting point is much more significant than on boiling point.

The presence of hydrogen donor group(s) in the molecules will be expected to increase the melting point since they can hydrogen bond intermolecularly with hydrogen acceptors from other molecules. This interaction in turn increases the binding forces in the crystal. Thus, more energy is required for its dissociation.

The positive value of the coefficient of IHB-4 can be explained by the fact that the presence of amine or hydroxyl group at the 2 or 6 position of pyridine, or a 2-pyridone system, results in the formation of cyclic dimers held together by parallel intermolecular hydrogen bonding, rather than the formation of a four membered intramolecular hydrogen bonded ring.

The intramolecular hydrogen bonding parameters reflect the influence of the individual intramolecular hydrogen bond to the whole prediction equation. Each gives a negative value for the regression. Intramolecular hydrogen bonding can be formed if the hydrogen bonding group(s) is adjacent (ortho) to the hydrogen acceptor(s) such as halides, nitro, etc. Therefore, there is a reduced ability to interact with the hydrogen acceptor from other molecules.

Another parameter introduced in this study is O-BIP which is used for biphenyl derivatives that possess substituent(s) at the 2, 2', 6, or 6' positions. The regression value for this parameter is negative, and the *T* test shows that it is significant. As we mentioned previously, the presence of one or more substituents at the positions above would change the dihedral angle of the two phenyl rings.²⁴ The more substituents present the greater the dihedral angle. Thus, O-BIP would be expected to decrease the planarity of the molecule which in turn decreases the packing efficiency.

SUMMARY

We have developed the approaches that employ group contributions of the enthalpies of boiling and melting to estimate the boiling point and melting point of rigid aromatics based on their molecular structures.

We have also studied the effect of intramolecular hydrogen bonding on the boiling and melting temperatures as well as the effect of substituent(s) present at the 2, 2', 6, and/or 6' positions of biphenyls on the melting points.

The equations developed have been shown to calculate the boiling points of 246 rigid aromatic compounds with a standard error of 17.3 K and the melting points of 1186 aromatics with a standard error of 37.7 K.

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Supplementary Material Available on Request from Author: Table containing all compounds with their parameters, experimental/calculated data, and residuals.

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