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CALORIMETRIC INSTRUMENTATION FOR STUDIES OF BIOPOLYMER MODEL COMPOUNDS

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Abstract - To facilitate the interpretation of results from thermodynamic experiments on biopolymers it is important to have available data for model systems. A survey is given of different types of instruments used in such model studies: solution calorimeters, including instruments suitable for slightly soluble compounds, calorimeters for mixing or dilution processes, heat capacity calorimeters and vaporization calorimeters.

INTRODUCTION

It was not until quite recently that application of calorimetric techniques to biochemical thermodynamic problems became more than a feature of a few specialized laboratories. This late adoption, in biochemistry, of one of the most important thermodynamic tools, is probably due to the fact that suitable calorimeters have not been generally available very long. An additional reason may be that results of calorimetric measurements on biochemical systems are usually not very easy to interpret on a molecular level - even if the system studied is made up by well-defined and highly purified compounds. Derived data are often discussed in terms of possible contributions from hydrogen bonds, hydrophobic interactions, conformational changes, steric effects, etc. However, such discussions are frequently highly speculative and far from the level of analyses made e.g. for gas phase data on simple compounds. One approach towards a deeper understanding of thermochemical results for biopolymer systems is to study the properties of models of different complexity. Within a series of model compounds the structure can be varied systematically and correlations can be made between thermodynamic data, well-defined structural features and medium effects. It is probably not possible to increase gradually the complexity of a model with the intention of reaching finally the level of a biochemical system, but there are still large areas on the most basic level which remain to be covered.

Transfer processes contribute very substantially to the overall thermodynamic picture of most biochemical processes. As a characteristic example we may look upon a simple protein ligand binding reaction. At the binding process the ligand molecule is transferred from bulk water to the binding site of the protein where more or less specific non-covalent 'bonds' are formed. Prior to the reaction the ligand is solvated by bulk water and we have reason to believe that the properties of the water surrounding the ligand molecule are affected by the properties of the ligand. Before the reaction the binding site may accommodate a certain number of water molecules which probably do not have the properties of bulk water. As a result of the binding process we may expect that (part of) the water shell initially surrounding the ligand molecule, and the binding site, will be transformed to bulk water. Further, a conformational change of the protein may cause a substantial change in the contacts between it and the water. Such changes will give rise to large contributions to the measured gross thermodynamic changes.

Other typical biochemical processes where medium effects are believed to play a dominant role are protein unfolding processes. For such processes groups from the interior of the folded protein (not the least hydrophobic groups) will be brought in contact with the bulk water and as a result the thermodynamic properties of the system will be affected.

An area of particular importance in current model studies is therefore the one dealing with interactions between water and other solvents and solutes, including the thermodynamics of transfer of compounds and groups between

water and different non-aqueous media. This paper will concentrate on calorimetric instruments and techniques useful for studies of solute - solvent interactions. Such experiments primarily involve determination of enthalpies of solution, dilution (mixing) and vaporization and of heat capacities and heat capacity changes. Compounds studied mainly consist of series of simple non-biochemical organic compounds (hydrocarbons, alcohols, amines, carboxylic acids, amides, phenolic compounds, etc.) and building stones for biopolymers such as amino acids and peptides, sugars and nucleotide bases. Calorimeters useful for measurements of solution processes are of course frequently also suited for measurements of chemical reactions (e.g. ionization and hydrolysis processes), which also are of great value in bio-thermochemical model work.

From solution data for a compound in different solvents data for the transfer between the solvents can be calculated. Combining data for solution processes and corresponding values for vaporization processes leads to values for the transfer between the gas phase and the solution. Partial molar heat capacities for solutes ($C_{p,2}$) are often calculated from data for the heat capacity change at the solution process ($\Delta C_{p,2}$, obtained from solution measurements at different temperatures), and the heat capacity of the pure compound (C_p^*) in the state used in the solution experiment

$$C_{p,2} = \Delta C_{p,2} + C_p^* \qquad (1)$$

Alternatively $C_{p,2}$-values (or the apparent quantity) can be obtained from heat capacity measurements performed directly on the solution.

Thermochemical studies on biochemical models can usually be looked upon as part of the general field of thermochemistry and as such, the results will have their full value even if it turns out that a particular study is of no immediate importance for the biochemical field. It is then required, however, that the work is done systematically and that the data are determined with adequate accuracy. It is therefore desirable that studies on simple model compounds are made with the highest possible accuracy even if this is not judged to be necessary for the biochemical problem which may have been the reason for initiating the model study.

Depending on the type of process studied the design of the calorimetric instrument can vary. Also different instruments are designed for the same kind of measurements. Very sensitive calorimeters requiring small quantities of material (in the order of a few cm^3 or less) are often called 'microcalorimeters'. However, there is no sharp division line between conventional calorimeters and 'microcalorimeters' and in this paper there will not be made any particular distinction between them. It is not the purpose of this paper to give a comprehensive review of all calorimeters described which can be of interest for studies of biochemical models. Rather, a few important and currently typical examples of instruments will be treated. For some of the generally well known calorimeters description will be very brief even if their importance for model compound work is very significant. More attention is given to a few designs which are of particular importance for solution of slightly soluble compounds including liquids, solids, as well as gases.

SOLUTION AND REACTION CALORIMETERS

In the literature there are described a large number of different designs of solution and reaction calorimeters suitable for aqueous systems and for other solvents. Many interesting model compounds are readily available in large quantities and are easy to dissolve. In such cases it is usually advantageous to use conventional 'macro' calorimeters, which often give the most accurate results. A typical example of a precise general purpose instrument is the LKB 8721-1 reaction and solution calorimeter (cf. Ref. 1) (LKB-Produkter, Bromma, Sweden). This calorimeter, which has been used in many solution studies of significant interest in biochemical model investigations, is of the isoperibolic type. The calorimetric vessel consists of a thin-walled 100 ml (or 25 ml) glass vessel fitted with a thermistor, a calibration heater, and a stirrer which also serves as a holder for a cylindrical 1 ml glass ampoule containing the reagent, Fig. 1.

The vessel is contained inside a metal can submerged in a thermostated ($\pm 0.001^{\circ}C$) water bath during an experiment. The glass ampoule has very thin end walls which can be broken against the sapphire-pointed glass pin. The

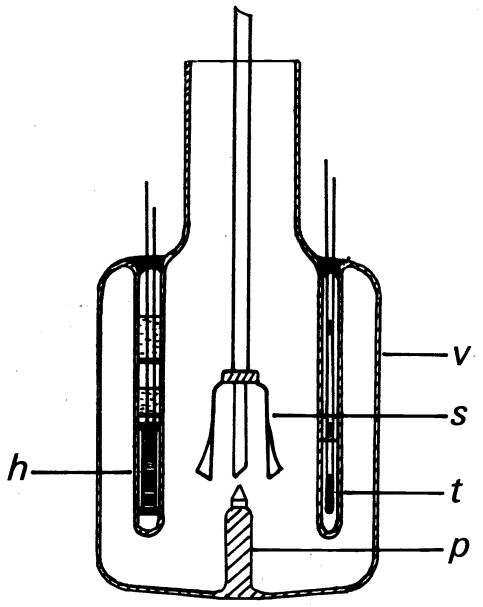

Fig. 1. A typical reaction vessel for a conventional solution calorimeter (LKB 8721-1).
(v) thin-walled glass vessel, volume 100 ml, (s) stirrer and ampoule holder, (t) thermistor, (p) sapphire-pointed glass pin for breaking of the ampoule, (h) calibration heater.

thermistor forms one arm in a conventional dc Wheatstone bridge allowing temperature differences of 5×10^{-5} °C to be detected. In an experiment the bridge may be kept balanced by manual operation or the off-balance signal can be directly recorded. With an adequate heat evolution (ca. 1 J/ml) it is possible to achieve a precision of 0.02% for fast processes. Typically, it is possible to measure accurately enthalpies of solution down to a solute concentration of about 0.02 mol dm^{-3}, which normally allows extrapolation to zero concentration.

In a titration version of this calorimeter liquid reactants can be added to the calorimeter vessel through a heat-exchange coil ending in a capillary tube inside the calorimeter vessel. The LKB Precision Calorimeter System also includes a closed-bomb reaction and solution calorimeter (cf. Ref. 2), which can be used for work up to 400 K.

Christensen et al. have made notable instrument developments in particular, of precise titration calorimeters, which have been commercially available through Tronac Inc., Oronto, Utah (cf. 3,4). The Tronac model 450 is an isoperibolic calorimeter, whereas the model 550 can also be operated as an isothermal thermoelectric heat pump calorimeter. In the latter instrument, the temperature is kept constant by balancing a variable heating against the heat production of the measured process and a constant thermoelectric cooling. This principle is suitable also for slow processes, cf. the gas solution calorimeter by Cone et al. (below).

Among the wide variety of other precise 'macro' solution calorimeters reference will here only be made to the isoperibolic large volume (300 cm^3) instrument developed by Shin and Criss (5). Reproducibility in electrical calibration experiments was reported to be 0.01% at a temperature rise of 0.13 K. A small vapour space above the liquid and a vapour trap make the calorimeter useful for measurements also with volatile non-aqueous solvents.

Calorimeters for mixing and dilution

In connection with investigations of different kinds of association processes or of deviation from ideal behaviour of solutions, it is of interest to perform mixing or dilution experiments. Often, conventional solution or titration calorimeters are suitable, but sometimes, it is desirable to use more sensitive instruments or to work with smaller quantities of substances. Some typical 'microcalorimeters' have found use in this connection. The LKB batch microcalorimeter (6) is a twin heat conduction calorimeter, Fig. 2. In each reaction vessel two liquid samples (typically 2 + 4 ml) can be mixed by rotation of the calorimetric block. A heat evolution of approximately 5 mJ can be determined with a precision of about 1 %. However, it should be noted that with the calorimetric vessels used, having open compartments and a rather large gas phase, one can easily introduce significant systematic errors from condensation/evaporation phenomenon accompanying the mixing process of volatile compounds. For aqueous solutions of non-volatile compounds changes of the gas phase composition can usually be neglected, cf. 7. Other typical 'micro-reaction calorimeters', e.g. the Calvet type of instruments (marketed by Setaram, Lyon, France) are also suitable for sensitive mixing experiments provided they are equipped with suitable mixing vessels and no problems occur with changes in the gas phase composition.

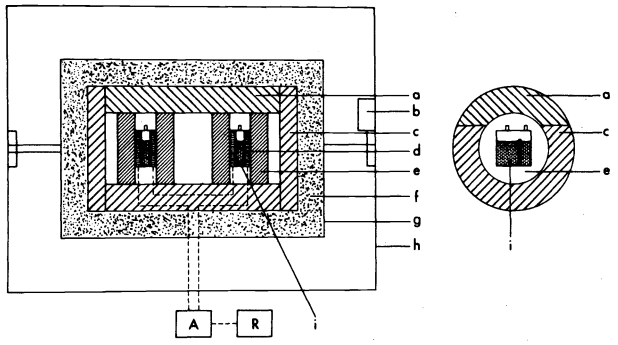

Fig. 2. Batch heat conduction calorimeter for mixing of two liquids (Ref. 6; LKB 2107).
(left) longitudinal section. (a) aluminium cover, (b) rotation motor, (c) aluminium heat sink, (d) semiconductor thermopiles, (e) aluminium block, (f) styrofoam insulation, (g) stainless steel container, (h) thermostated air or water bath, (i) reaction vessel. A is an amplifier och R is a recorder/integrator. (right) transverse section through calorimeter block.

With flow calorimeters two liquids can be mixed without presence of any gas phase and such instruments are therefore often ideal as mixing and dilution calorimeters. Among sensitive flow calorimeters the most widely used are the LKB flow calorimeter (8) and the Picker flow instrument (9,10). The latter instrument is marketed by Setaram. The LKB flow calorimeter is similar in design to their batch calorimeter shown in Fig. 2 but it contains a heat exchange unit inserted between the twin calorimetric vessels. Pre-thermostated liquids are pumped through the heat exchanger and are mixed in one of the calorimetric vessels. The sensitivity is given as 0.5 μW.

Fig. 3 shows the principle of a Picker mixing calorimeter fitted with single detector and a flow modulator. Liquids A_1 and B_1 are mixed at AB, forming the reaction mixture. After passing the heat exchanger (M) the mixture flows into A_2, where it acts as a reference liquid, flowing through the heat exchanger, R. This consists of a pump connected to the input side of a hydraulic commutator, which feeds two parallel branches M and R. These branches constitute the other half of the counterflow heat exchangers of the observation and reference cells. They merge at the detector block through a common return, where a heat-sensing device is located. The purpose of the hydraulic commutator is to alternately supply complementary flow segments of heat-exchanger liquid to the two branches of the heat exchanger. The result is that the heat sensor senses alternate segments of liquid from the two branches, thus elimi-

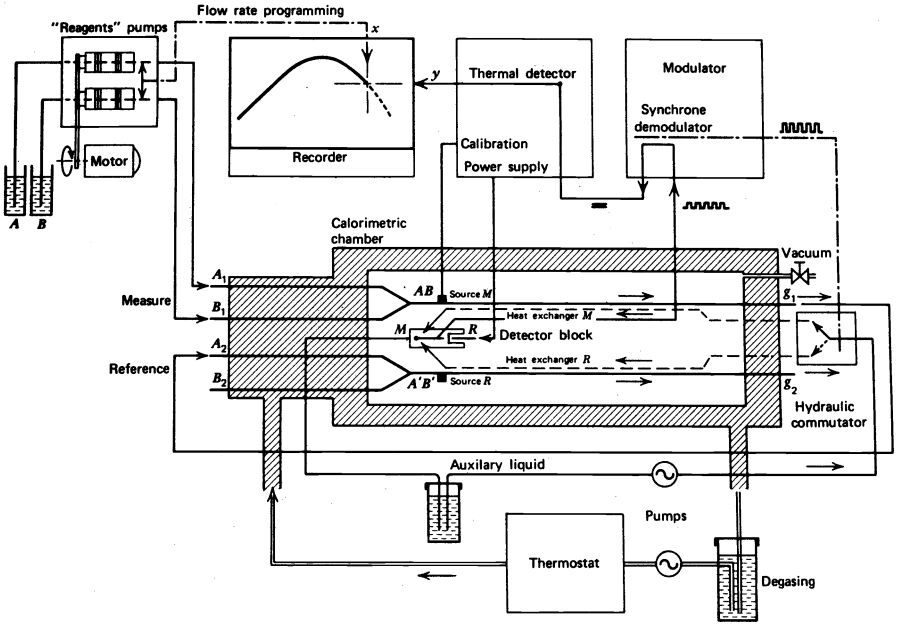

Fig. 3. Principle of the Picker flow mixing calorimeter (9,10). Courtesy of Setaram, Lyon, France.

nating the necessity for a second thermal detector. The flow-modulating device is an electromechanical vibrator that alternately (several times a second) opens and closes ports leading to the measuring and reference branches of the heat-exchange units. The thermal-detection limit of the calorimeter is reported to be 10^{-5} °C. A valuable feature of the calorimeter is its rapid response to changes in thermal power, and thus it is suitable for 'composition-scanning' experiments.

Solution of slightly soluble liquids

The thermodynamic properties of aqueous solutions of hydrophobic compounds are of great interest for the understanding of 'hydrophobic interactions' in biopolymer systems. Among the most interesting group of compounds in this connection are the hydrocarbons and other very slightly soluble substances. Solution calorimeters of the type discussed above are frequently not suitable for such measurements. This is particularly true for compounds combining a low solubility with a high vapour pressure, e.g. the lower liquid hydrocarbons. To overcome such problems the flow calorimetric vessel shown in Fig. 4 a, b was designed (11).

The vessel consists of three metal cylinders A, B and C, held together by a PVC press-fit joints, around which two concentric teflon tubes T_1 and T_2 are tightly wound. Two tightly fitting stainless-steel cylinders, D and E, are fitted concentrically over the inner rings (A, B, and C) and the tubing. The section incorporated in the upper cylinder, D, serves as a heat-exchange unit in contact with the metal block of a heat-conduction calorimeter of the type shown in Fig. 5. The section incorporated in the lower cylinder, E, serves as a mixing region. A small gap is left between cylinders D and E in order to reduce heat leakage. The mixing region (E) is situated in the heat-effect-sensitive area of the calorimeter. The sample, ca 5 mm^3, is introduced by means of a motor-driven Hamilton gas-tight syringe through a length of thin hypodermic needle. The needle can be 'injected' down tube T_1 and into tube T_2, via the flared opening, so that the end of the thin teflon tip, attached to the needle, is situated approximately one full turn inside tube T_2 (Fig. 4 b). A tight seal is made between the hypodermic needle and tube T_1. The solvent is pumped through tube T_1 and out through tube T_2. This arrangement, as well as avoiding the necessity of joints inside the calorimeter, provides adequate

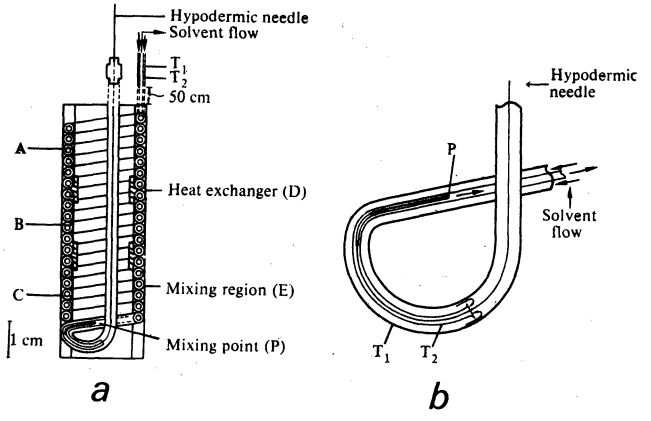

Fig. 4. Flow vessel for solution of slightly soluble liquids. (a) Section through the vessel. (b) Details of the mixing region. Reprinted from (11).

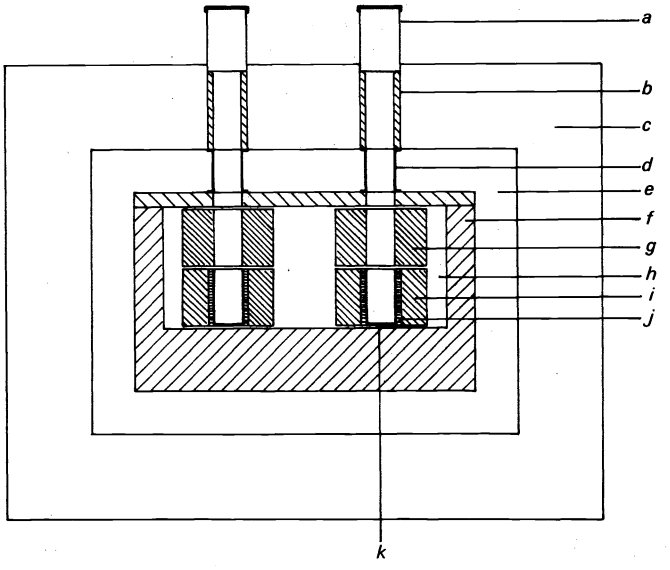

Fig. 5. Twin heat conduction calorimeter used for insertion of ampoules or flow vessels (12).
(a) steel tube, (b) copper constriction, (c) water thermostat, (d) steel tube, (e) air space, (f) main heat sink, (g) aluminium block, (h) air space, (i) air space, (j) thermocouple plate, (k) ampoule holder.

thermal equilibration of the incoming fluid even at high flow rates (50 cm^3 h^{-1}).

To illustrate the attainable precision for solution of hydrocarbons in water some values for ΔH_{soln} (25°C) and ΔC_p are shown in Table 1.

TABLE 1. Aqueous enthalpies and heat capacities of solution for some hydrocarbons at 25°C (13). Uncertainties are twice the standard deviation of the mean.

Compound	ΔH^{∞}_{soln}, kJ mol^{-1}	$\Delta C^{\infty}_{p,soln}$, J K^{-1} mol^{-1}
Benzene	2.08 ± 0.04	225 ± 5
Toluene	1.73 ± 0.04	263 ± 13
Ethylbenzene	2.02 ± 0.04	318 ± 13
Propylbenzene	2.3 ± 0.1	391 ± 25
Pentane	-2.0 ± 0.2	400 ± 70
Hexane	0.0 ± 0.2	440 ± 45

It is seen that for the lower aromatic compounds good precision was obtained whereas the low precision of the ΔC_p values obtained for pentane and hexane makes these values less valuable.

Recently a modified solution vessel has been built (14) where the sample is injected into a thin-walled teflon tube contained inside a stainless steel spiral. The vessel is molded into Woods metal and the assembly is contained in a brass can corresponding to the cylinder E in Fig. 4. The solvent flow arrangement is similar to that used with our gas solution calorimeter (below). The modified flow cell is easier to build and the electrical calibration can be made under more ideal conditions.

We believe that this type of solution instrument can be further improved. However, it is not probable that it will be possible to perform precise measurements of compounds which are as poorly soluble as e.g. heptane, solubility at 25°C ca. 3 mg dm^{-3}.

Solution of small quantities of slightly soluble solids

There are several groups of interesting biological model compounds which are solids and slightly soluble in water, e.g. peptides. Furthermore, frequently such compounds are difficult to obtain in quantities normally required in conventional calorimeters. Gill and Seibold (15) have described a flow calorimetric vessel, Fig. 6, aimed at taking care of such problems. The flow pattern is rather similar to that used in the instrument for dissolving liquids (Fig. 4).

Concentric teflon tubing provides the means by which the solvent is thermally equilibrated before it enters the calorimetric region. The end of the internal tube in the calorimeter provides the location where a solid sample can be inserted into the path of flow. The insertion is made by a special probe, which isolates the sample from the solvent until flow is initiated. The heat of solution is detected by a Tian-Calvet calorimeter block.

The insert probe (see Fig. 6b) consists of a thin wall teflon tubing inside of which is a pull rod. The pull rod is a 24-gauge needlestock (at the end, a piece of 22-gauge needlestock has been attached). This piece fits closely inside the insert tubing and can seal the valve hole. The direction of liquid flow in the apparatus is up the inner teflon tube, through the glass sample cell and valve hole of the probe, and finally out the outer teflon tube.

In a typical experiment the following procedure is used. Liquid is pumped through the concentric teflon tubes at a high flow rate to remove any trapped air. Liquid is allowed to flow up through the insert tube to ensure it is filled, flow is stopped, the outlet tube is closed, and the inlet valve is opened to the atmosphere so that the probe can be inserted and the insert seal made. The pull rod is then pulled up so as to expose the valve hole but not wet the sample. After equilibration the inlet valve is turned to connect the inner teflon tube with the pump flow line, the flow outlet is opened, and the pump is turned on to initiate flow. The sample cell is charged with about

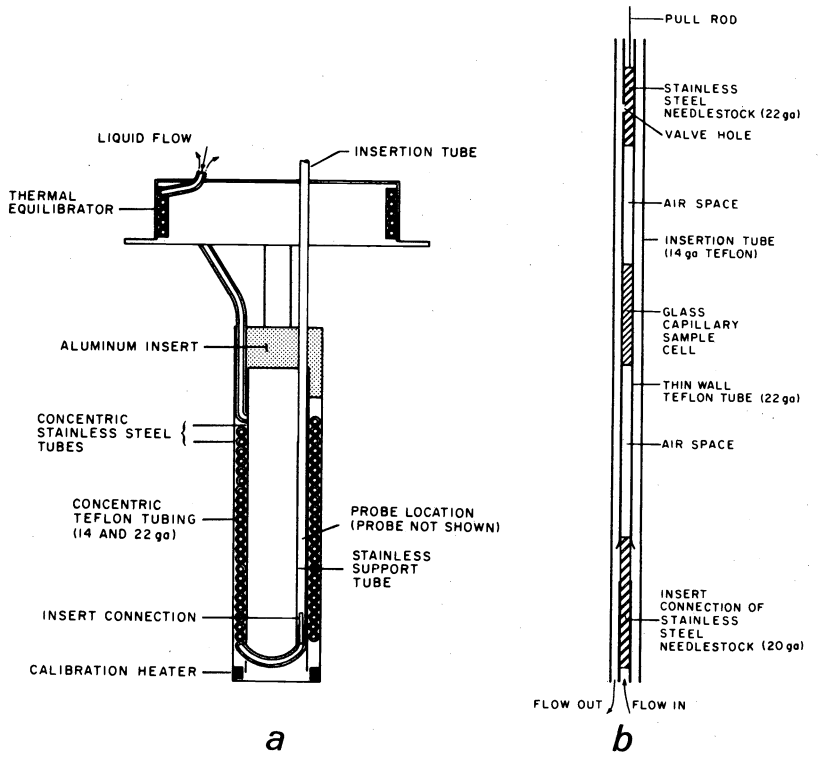

Fig. 6. Flow vessel for solution of small samples of slightly soluble solids (Gill and Seibold).
(a) Section through the vessel. (b) Expanded view of the solid insert probe. Reprinted from (15).

1 mg of substance and the solvent flow rate was about 10 cm^3 h^{-1}. Precision of measurements were 1 - 2 % for compounds of the type diketopiperazine, thymidine and inosine.

The development of a similar instrument is in progress in our laboratory.

Solution of slightly soluble gases

There are a number of gaseous compounds for which accurate thermodynamic data in aqueous and non-aqueous solutions are needed; not the least in connection with investigation of the hydrophobic effect. Such compounds include in particular the rare gases and the saturated and unsaturated hydrocarbons. Until very recently there have hardly been performed any direct calorimetric measurements of solution of such compounds.

Gill and coworkers have described a sensitive differential calorimeter which can be used to measure directly the heat of reaction between a gaseous compound and a substance in solution (16). The rate of gas absorption is followed manometrically.

Cone et al. (17) have recently described a gas solution calorimeter based on the Tronac Model 550 Calorimeter System using a thermoelectric heat pump (cf. above). The reaction vessel is shown in Fig. 7. It is built of copper and has a capacity of 45 cm^3. The Peltier cooler and resistance heater assembly c maintains temperature control in the reaction vessel. The resistor is placed inside the bottom of a copper cooling probe which extends into the reaction vessel. Degassed solvent is transferred into the calorimeter vessel through a valve, g. The vessel is completely filled with solvent leaving very little or no vapour space. (Before the gas injection the system is under vapour pressure from the solvent alone.) In a solution experiment the gas is injected from a syringe through the septum, h.

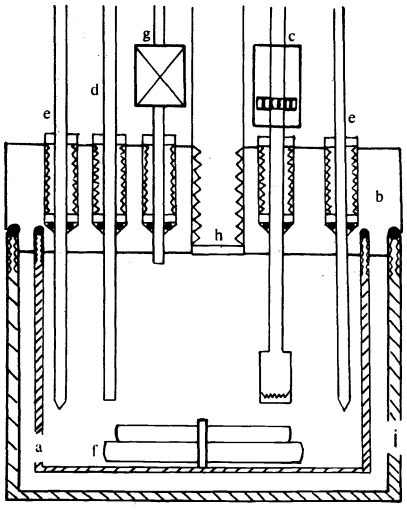

Fig. 7. Schematic diagram of a gas solution calorimeter (Cone et al. (11)).
(a) Reaction vessel, (b) cap with feed-throughs, (c) Peltier cooler-resistance assembly, (d) calibration heater, (e) thermistors, (f) magnetic stirrer, (g) valve for solvent introduction, (h) septum, (i) outer nylon jacket. Reprinted from (17).

Results were reported for enthalpies of solution of several hydrocarbon gases into some organic solvents. In forthcoming reports the authors will present results using water as the solvent.

As is being reported at this meeting by S.J. Gill we have at our laboratory recently designed a flow calorimetric vessel for solution of gases (18). The instrument is in some respect similar to our calorimeters described above for solution of slightly soluble liquids, Fig. 4, 5. Fig. 8 shows schematically the solution zone of the flow vessel, which is made of glass. During a measurement a constant flow of gas free solvent (50 $cm^3\ h^{-1}$; so far only water has been used as solvent) is thermostated by a counter current flow arrangement. A constant flow of gas is introduced into the vessel through a stainless steel syringe (s) and a gas bubble is formed (g). The solvent flow (w) passes between the walls of the glass tube and the gas bubble. A constant gas solution rate (i.e. a constant volume of gas bubble) will be established provided that the ratio of solvent and gas flow rates is appropriate. The solution part of the vessel is molded into a brass can with Woods metal and positioned in the thermopile zone of a heat conduction calorimeter (Fig. 5). As a steady state situation is obtained enthalpies of solution can be calculated from the thermal power recorded and the gas flow rate. Aqueous solution measurements have been made at different temperatures for Ne - Xe and for CH_4 - n-C_4H_{10}. Precision obtained for the enthalpy values are typically in the order of 1 - 3 %.

HEAT CAPACITY CALORIMETERS

In work with models for biopolymers heat capacities for solutes are often of primary interest. However, it may be noted that accurate heat capacities for the pure compounds are needed if partial molar heat capacities are to be calculated from ΔC_p-values obtained from solution measurements, cf. above. Existing heat capacity data for pure compounds were often determined by use of low temperature adiabatic shield calorimeters, see e.g. (19), primarily designed for entropy determinations. Usually such instruments require large sample quantities, but recently designs suitable for 10 g samples have come into use (20). Any isoperibolic (or adiabatic shield type) solution calorimeter can normally be used for heat capacity measurements of pure liquids and solutions. From the electrical calibration constants for the system charged

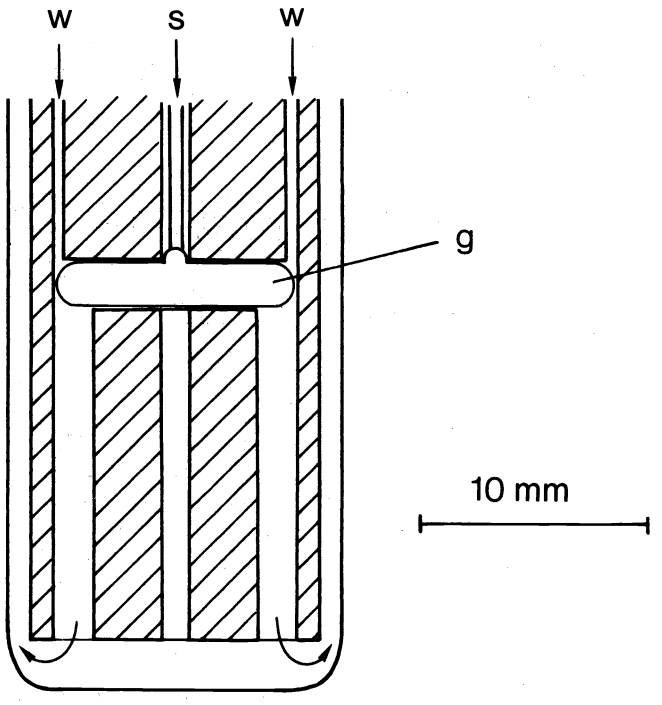

Fig. 8. Schematic view of the solution zone of a new flow solution calorimeter for slightly soluble gases (18).
(w) Solvent (water) flow, (s) syringe for introduction of gas, (g) gas bubble.

with a sample solution, its heat capacity can be calculated. Under suitable conditions (a precise calorimeter, similar physical properties for the reference and the sample liquid, low volatility of the liquids, and a rather large vessel (ca. 100 cm^3) it is with this method possible to measure the heat capacity of liquids with an accuracy significantly better than 0.1 %.

Picker (21) has designed a very precise flow heat capacity calorimeter using a novel principle shown in Fig. 9. The instrument is commercially available from Setaram. The design of the instrument is in many respects similar to the flow mixing calorimeter shown in Fig. 3.

It consists of two flow cells, each equipped with a heater and a thermistor. The reference liquid A (e.g. pure water) is thermostated, passed through the flow cell (1) where it is heated, Z_1, and the temperature T_1 is measured. The liquid is again thermostated and is passed through the second closely identical flow cell (2) where heat is supplied, Z_2, and the temperature T_2 is measured as in cell (1). Once the steady-state condition has been reached, liquid B (e.g. a dilute aqueous solution) is circulated, but because of the length of the flow circuit, there is a time interval during which different liquids are passing through the two cells. A thermal feedback procedure maintains the same temperature gradient in both flow cells regardless of differences in heat capacities of the two liquids. The instrument thus measures the change in power input ΔP that is necessary to maintain the final temperature of the liquid in the 'working flow cell' equal to that of the reference liquid in the other cell. Knowing the densities ρ^o and ρ for liquids A and B, respectively, and the heat capacity C_p^o of liquid A it is possible to calculate the heat capacity C_p for liquid B:

$$\frac{C_p}{C_p^o} = (1 + \frac{\Delta P}{P})\frac{\rho^o}{\rho} . \qquad (2)$$

It is thus not necessary to know the flow rate exactly nor the temperature rise in the flow cells, ΔT. The derived C_p value is a mean value referring to the temperature interval ΔT. This is usually a few K.

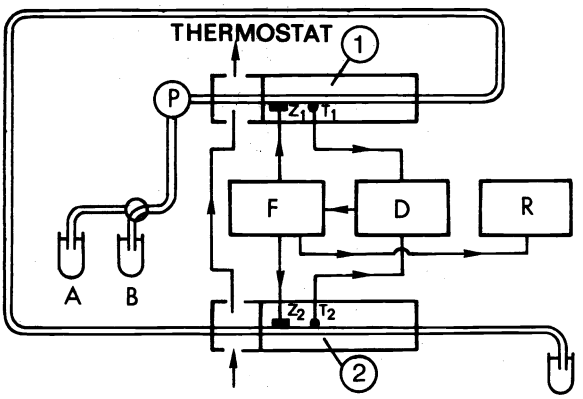

Fig. 9. Principle of the Picker flow heat capacity calorimeter. (A) solvent, (B) solution, (Z_1,Z_2) heaters, (T_1,T_2) thermistors, (P) pump, (F) feed back, (D) null detector, (R) recorder.

The precision of the measured heat capacity differences is typically 0.5 % but is has been shown that the results can be affected by a systematic error due to heat leak between the heating element in the calorimeter and the calorimetric jacket (22). The error can be corrected by use of an empirical factor.

In our laboratory we have designed a precise drop heat capacity calorimeter for small samples (< 1 g) which may be solids or liquids (23), Fig. 10. The calorimeter assembly consists of two main parts: a 'furnace' F for temperature equilibration of two sample ampoules and the receiving twin calorimeter block C of the heat conduction type (similar to that used with the solution calorimeters described above, Fig. 5). The sample, enclosed in a steel ampoule, and a reference ampoule, are thermostated in the furnace at a well defined temperature θ_i. In an experiment the ampoules are dropped simultaneously into the receiving calorimeter, which is kept at a lower temperature θ_f. The twin calorimeter thus measures the difference between the heat quantities transferred by the two ampoules. From the difference in experimental results carried out with the sample ampoule filled and empty, the heat quantity transferred by the sample can be determined and the mean heat capacity for the sample in the temperature interval θ_i to θ_f (ca. 10 K) can be calculated. The furnace consists of a copper block on which a heater is wound. Through the block there are two vertical holes where the sample ampoule (f) and the reference ampoule (e) are thermostated. Samples are contained in cylindrical steel ampoules which are transferred from the furnace to the calorimeter by free fall. They are brought back to the furnace by a magnetic lift. The calorimeter, which preferably is calibrated with water as a standard substance, has a precision of 0.01 % and an estimated accuracy of better than 0.1 %.

Temperature scanning heat capacity calorimeters (e.g. 'differential scanning calorimeters', DSC) are of great importance in studies of biopolymers, in particular for investigations of thermal transitions. They have also found use as heat capacity instruments in model compound work. Properties of these instruments are treated in the paper by P.L. Privalov.

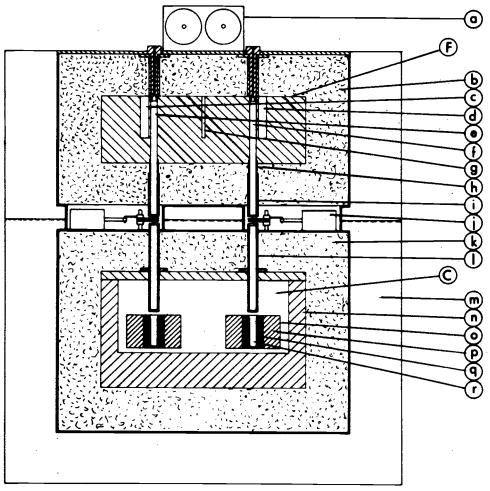

Fig. 10. Schematic view of a twin drop heat capacity calorimeter for small samples (23).
(F) furnace, (C) twin calorimeter, (a) mechanical lift, (b) insulation, (c) hole, (d) hole for the quartz probe, (e,f) holes for equilibration of the ampoules, (g) hole for the thermistor, (h) copper tube, (i) plastic tube, (j) electromechanical shutter, (k) insulation, (l) perforated plastic tube, (m) water thermostat, (n) main heat sink, (o) calorimetric unit, (p) aluminium block, (q) thermocouple plate, (r) receiver for the ampoules. Reprinted from (23).

VAPORIZATION CALORIMETERS

There are at present very few laboratories where enthalpies of vaporization measurements are performed. Investigators needing enthalpies or heat capacities for vaporization processes often rely upon data from vapour pressure measurements (van't Hoff values) or simply use estimates based on empirical rules. However, both van't Hoff data and empirical estimates can easily lead to significant errors. In particular this is the case for associated liquids and for solids and calorimetric determinations should therefore be encouraged. A wide range of vaporization calorimeters has been described, some of which will be referred to here.

In our laboratory vaporization calorimetry has been in use for many years, mainly involving two types of instrumentation. One is suitable for substances with vapour pressures in the range of 0.05 - 25 kPa (24). This instrument, which is included in the LKB calorimeter system, requires 50 - 100 mg of substance per experiment and is designed for operation preferably at room temperature. Another instrument (25), also mainly used at room temperature, can be used for compounds with very low vapour pressures. It is routinely used for compounds in the vapour pressure range of $0.1 - 10^{-5}$ kPa. Recently, a new instrument was designed (26), which is suitable for work on 5 mg samples from room temperature up to 420 K for compounds with vapour pressure in the range 0.01 - 1 kPa.

Another recent design reported by Majer et al. (27) can be used for a similar temperature range for compounds having vapour pressures between 1 - 200 kPa. Other recent designs have been described by Konicek (28) and Kusano and Saito (29).

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