

TWO CALORIMETRIC METHODS FOR INVESTIGATING DANGEROUS REACTIONS

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Two novel calorimeters are described which enable safety investigations on reaction mixtures and reactive substances. The usual features of large scale batch reactors (stirring, temperature control, reflux) can be simulated in the isothermal reaction calorimeters, whereby the instantaneous heat release, the total heat of reaction and the heat transfer coefficients can be calculated. The second calorimeter features adiabatic as well as isothermal operation and can find the lowest temperature at which a detectable exothermic reaction begins in a small test sample. Examples of the practical application of both apparatus are given.

INTRODUCTION

One of the biggest hazards in the chemical industry arises from the considerable energy which may be partly or wholly released during a production process due to exothermic chemical reactions or physical changes. Such reactions are normally controlled by removal of the heat energy released.

Situations where control has been lost can be divided into two categories:

- Introduction of a new procedure, change in the manufacturing instructions, or possibly the use of new or modified equipment. The immediate danger source is the exotherm of the intended reaction leading to the desired product. Such heat release is unavoidable and rarely reducible in intensity. Should the reaction equipment be incapable of removing the liberated heat then the temperature will increase, generally resulting in an acceleration of the reaction. A secondary effect, namely the initiation of undesired reactions leading to loss of the intended product, can now arise. Additional heats of decomposition or formation may now rapidly accumulate to destructive levels.
- Exceptional circumstances which could even occur in well proven processes. These include changes in the quality of starting materials, technical defects in the equipment, unexpected occurrences, confusions, human errors etc. Whilst all these influences cannot be realistically avoided, at least the knowledge of the temperature at which a dangerous decomposition begins and of the consequences of the worst possible conditions which could occur, provides a criteria for "safety".

REACTION CALORIMETER

The first type of dangerous situation is now considered. The ability to control a given reaction depends on the knowledge of the heat of reaction and its rate of release on one hand, and the available cooling capacity together with the reactor heat transfer coefficient and its dependence on composition and temperature, on the other. Such information may be obtained directly through calorimetric measurements, whereby the influence of the industrial equipment parameters on the reaction course should be simulated. Bearing in mind that $\pm 5\%$ accuracy is fully acceptable, the following main features of production equipment are selected,

- intensive stirring
- accurate temperature control
- feed of reactant(s)
- reflux boiling

which are generally not available in other calorimetric apparatus. The measurement should not only provide the total heat of reaction but also the heat release profile and the heat transfer coefficient.

The calorimeter designed and developed for the above purpose consists of a normal laboratory 2 liter reaction flask built into a specially constructed bath and equipped with a stirrer, feed vessel and reflux condenser. Diagram 1 illustrates the principle of the fast reacting heating/cooling system which is essential for good temperature control. The heat exchange medium (silicone oil) leaves the rotating bath, passes through a cooler, (producing an almost constant outlet temperature) and finally through an electric flow heater before returning to the bath. The temperature controller is thus able to effect rapid heating of the circulating medium by changing the power of the heating element. The reflux cooler is connected to a separate cooling water system.

The instantaneous heat flux Q_r , is measured using the following heat balance on the cooling bath and condenser,

$$\dot{Q}_r = G_B C_B (T_{IB} - T_{OB}) - G_F C_F (T_{IF} - T_{OF}) + V_B \rho_B C_B \frac{dT_B}{dt} + V_K \rho_K C_K \frac{dT_K}{dt}$$

The symbols are defined in Fig. 1.

The terms involving the first derivatives of the reaction and bath temperatures account for dynamic changes of heat content in the system. The total reaction heat is obtained by integrating the measured heat rate over the chosen time period.

The difficulty in attaining good control and measurement with the low flow rates (about 50-100 l/h) necessary for obtaining measurable temperature differences, is overcome by rotating the bath, which consists of a Dewar vessel having the smallest possible gap between the reaction flask and its inner wall. The resulting increase in bath turbulence produces better heat transfer and temperature homogeneity, higher temperature differences and improved control.

Despite several years of successful operation using the above technique, further development has evolved a better method, presently nearing completion.

For data processing, an analog electronic circuit or any type of on-line computer can be used. A recorder is used to register the instantaneous heat release rate and the total reaction heat. The equation,

$$Q_r = UA(T_K - T_{OB})$$

determines U , the heat transfer coefficient, between the reaction mixture and the bath, and uses the known bath heat transfer area A , and the measured values for the heat rate, Q_r , and the temperatures, T_K and T_{OB} .

Practical application of the three measured values, Q , A and U , are given in examples below.

Some technical specifications

Volume reaction flask	2 l
Volume bath	ca 770 ml
Temperature range	-30 to 200°C
Heating/cooling capacity	ca 1 kW
Smallest measurable heat flux	1.5 kcal h ⁻¹
Peak sensitivity	20 cal
Temperature control accuracy (at 5°C with 40 W disturbance)	0.8°C

Reproducibility (standard deviation)	1.02%
Overall time constant for heat measurement:	
digital system	ca. 5 sec
analog system	ca. 30 sec

Examples of the Uses of the Calorimeter:

After successful testing, the calorimeter was installed in the Safety Laboratory of the Pharmaceutical Chemical Development Department of Sandoz Ltd. With the described apparatus approximately 260 reactions have been tested.

1. Reaction of a Ketone with Sodium Borohydride (clarification during early phase of process development)

As specified in the reaction procedure, all the solid sodium borohydride is added at once to the ketone in the flask. The reaction starts immediately and according to laboratory estimates is highly exothermic. In order to specify the production plant for this reaction, it is necessary to know the maximum spontaneous heat release rate achieved under isothermal operation and the duration of the reaction. The isothermal temperature range is 50 - 60°C. The results of the calorimetric measurements are given in Fig. 2., the reaction profile being indicated by curves a and b. Though the total heat is representative of a moderately exothermic reaction, the reaction rate is relatively fast and leads to a correspondingly high heat release rate. Observations of this reaction in normal laboratory apparatus give a false picture, since they indicate a high heat of reaction instead of a high heat release rate.

The suitability of this reaction at production scale is simply assessed by consideration of the available cooling capacity. Generally speaking this reaction can be performed at 50°C in batch reactors (having simple cooling jackets) of approximately 50 - 400 l capacity. At 60°C however production of this scale is no longer possible.

Diazotisation (Measurement for Scale-up into Production)

The cooling capacity of large batch reactors becomes a limiting factor when diazotisation reactions are carried out at 0°C. The reaction itself is easily controlled by the addition rate of the nitrite but the cooling capacity of the reactor could become critical though a combination of high heat release and poor heat transfer coefficient. It is noticeable that the reaction product is a solid precipitate and that the reaction mixture changes progressively from a liquid into a thick suspension.

The plot of heat release against time is proof that this reaction procedure can be fully controlled. The reaction is fast and stops immediately at the end of the nitrite addition. The heat of reaction is 29 kcal/mol. The heat transfer coefficient changes significantly during the reaction, beginning with a typical value for aqueous solutions and reaching half this value towards the end of the reaction. From the determination of the cooling capacity of the reactor at 0°C the addition rate and duration can be calculated.

Methylation (trouble-shooting at Pilot Plant Stage).

According to the laboratory reaction procedure the starting products, acetone and sodium carbonate, are mixed in the reaction vessel at 0°C and methanol is added for 1 hour. During a trial in a 250 l batch reactor a temperature run away occurred until the boiling point of the acetone was reached - even with full cooling applied. Consequently the reactor contents foamed out of the vessel and the batch was lost. Therefore the cause of the incident had to be explained and a means of safe production in the pilot plant found.

On repeating the reaction in the calorimeter, the maximum heat generation was measured, and the heat transfer coefficient found to remain at a value normal for aqueous solutions. The cooling capacity of the relevant 250 l reactor at 0°C (calculated from an experimentally measured cooling curve), was found to be 3 times less than the scaled-up heat generation rate. Thus the cause of the incident was easily explained.

For single exothermic reactions, the heat release rate is proportional to the rate of reaction. In the above case a kinetic expression of the form,

$$r = kA^m B^n$$

$$\dot{Q} = rV \Delta H_R$$

was fitted by non-linear regression to the measured heat profile. After successful identification of the kinetic parameters k , m and n , they were used to predict a safe addition rate enabling isothermal operation of the large scale reaction.

SAFETY CALORIMETER

The first part demonstrated how the reaction calorimeter aided the safe operation of some chemical reactions - assuming that production specifications (quality of starting materials, operating instructions, reaction conditions, etc.) were adhered to, and that the equipment was functioning correctly. In practice however such assumptions cannot be guaranteed. Case studies reveal that the most dangerous abnormal conditions occur due to the failure of cooling systems or the uncontrolled rise in reaction temperatures, which in the extreme is represented by a reaction progressing under adiabatic conditions. The latter situation is a generally accepted method for danger assessment, the test method used being called adiabatic storage or heat accumulation.

To detect whether the exotherm lies in a temperature range of practical significance, the above examination should be combined with a further test - the determination of the lowest temperature at which an exothermic reaction can be identified. For both tests a safety calorimeter, commercially called 3IKAREX, has been developed. It consists of a test-tube which fits into a cylindrical jacket, through which air is circulated by means of a blower, and whose temperature is controlled by a heater (Fig. 3). By means of a second heating element wound upon the test-tube wall and a sensor inside the tube, the temperature of the test sample can be measured and controlled. This basic equipment enables three different tests to be made.

Quasi-isothermal Calorimetry

The sample is placed in the test-tube and the jacket temperature held constant. On attaining equilibrium, a temperature difference between sample and jacket may be obtained, which in the no measurable heat case is zero, but becomes positive when the amount of heat released due to a chemical reaction is significant enough to be detected by the apparatus.

To identify the first exotherm, equilibrium temperature differences so measured may be plotted against the corresponding sample temperature (Fig. 4). Through calibration of the system the heat evolved can be obtained from the temperature difference, as indicated by the left hand scale.

Adiabatic Calorimetry

The progress of a self-heating reaction is followed by making the sample temperature the set-point for the jacket temperature controller. The sample surroundings are therefore maintained at the same temperature as the sample itself, heat transmission by conduction is thus minimised, and the extreme case of inadequate cooling is simulated.

Perfect adiabatic conditions are rarely obtained in practice due to heat losses, or due to heat dissipated from an agitator in a reactor. These effects may be simulated in the safety calorimeter by establishing a constant temperature difference between the sample and jacket during the whole experiment.

Isothermal Calorimetry

In the third test the sample temperature is held constant by establishing a constant rate of heat exchange to the jacket (held about 50-100°C below the sample) and controlling the test tube heating coil to compensate for the excessive cooling. By measuring this electrical heating energy a negative copy of the reaction heat profile is obtained.

This measurement is currently not widespread in safety laboratories, despite yielding some very important information. Firstly, reactions having a real induction period can be distinguished from those in which the Arrhenius temperature dependence produces an extremely slow reaction, and secondly, the reaction heat profile at constant temperature is an important parameter for equipment design. The test provides additional, further interesting data about the chemical kinetics of dangerous substances including their temperature dependence.

Technical Data

Sample size: 10-30 g

This quantity of material is generally available at the research or the development stage of a project, whereas some other testing equipment requires an undesirable, larger amount.

Normal laboratory or production techniques such as stirring and component addition can be applied.

Test requires no special safety precautions.

The problem of obtaining a homogeneous sample, which occurs in some other methods, is eliminated.

Sensitivity: $\sim 10^{-4} \text{ cal s}^{-1} \text{ g}^{-1}$,

- or about 100 - 1000 times more sensitive than a differential scanning calorimeter.

Temperature range: 0 - 300°C

Pressure: 0 - 100 atm (0 - 0.1 MN/m²)
(replacing the test-tube with an autoclave)

Heating-up rate: 0.2°C s⁻¹

Several of these calorimeters have been used routinely during the past years, and are manufactured and sold by the firm SYSTEM TECHNIK AG, CH-8803 Rüslikon, under the name SIKAREX.

An example of the numerous tests made is now outlined.

A batch of 1,5 dinitro-naphthaline, sulphur and sulphuric acid is prepared at room temperature and fed continuously for several hours into a second reactor where the reaction occurs at 120°C. This procedure was followed successfully without incident about 100 times before the presumably cold mixture exploded with devastating results. Investigations ruled out the possibility of wrong starting materials or erroneous heating of the vessel, but revealed that at about the same time the dinitro-naphthaline deliveries had been changed to a new supplier. The results of the tests in the safety calorimeter were as follows:

- a) The above mixture begins to react as low as 30°C, a fact which was not previously known. The vessel was therefore not cooled.
- b) Under adiabatic conditions the self-heating reaction finally becomes violent and produces a considerable quantity of gas.
- c) The reactivity of the dinitronaphthaline is strongly dependent on its quality. Despite satisfactory passing the analytical check however, the new delivery was shown to be more strongly exothermic, the reaction beginning at a lower temperature than with the previous material. Fig 5 shows the results of a quasi-isothermal test.

These three results irrevocably identify the cause of the explosion as being due to the different quality starting material and the absence of cooling.

The next examples illustrates how a dangerous occurrence was prevented.

A pharmaceutical intermediate was to be dried at 40°C. According to the results of a differential scanning calorimeter the substance was endothermic between 90°C and 100°C (melting point) and exothermic after 100°C. It seemed reasonable to assume that the difference between the drying temperature and the temperature at which the exothermic occurred was a sufficiently large safety margin, particularly through the existence of the melting point "barrier".

However, an investigation using the SIKAREX calorimeter showed that the first reasonable exothermic began at 45°C, and that under adiabatic conditions the temperature rose to 96°C, remained constant for a short period, and after rapid melting deflagrated violently (Fig. 6). Thus heating of this substance above 40°C could have been dangerous.

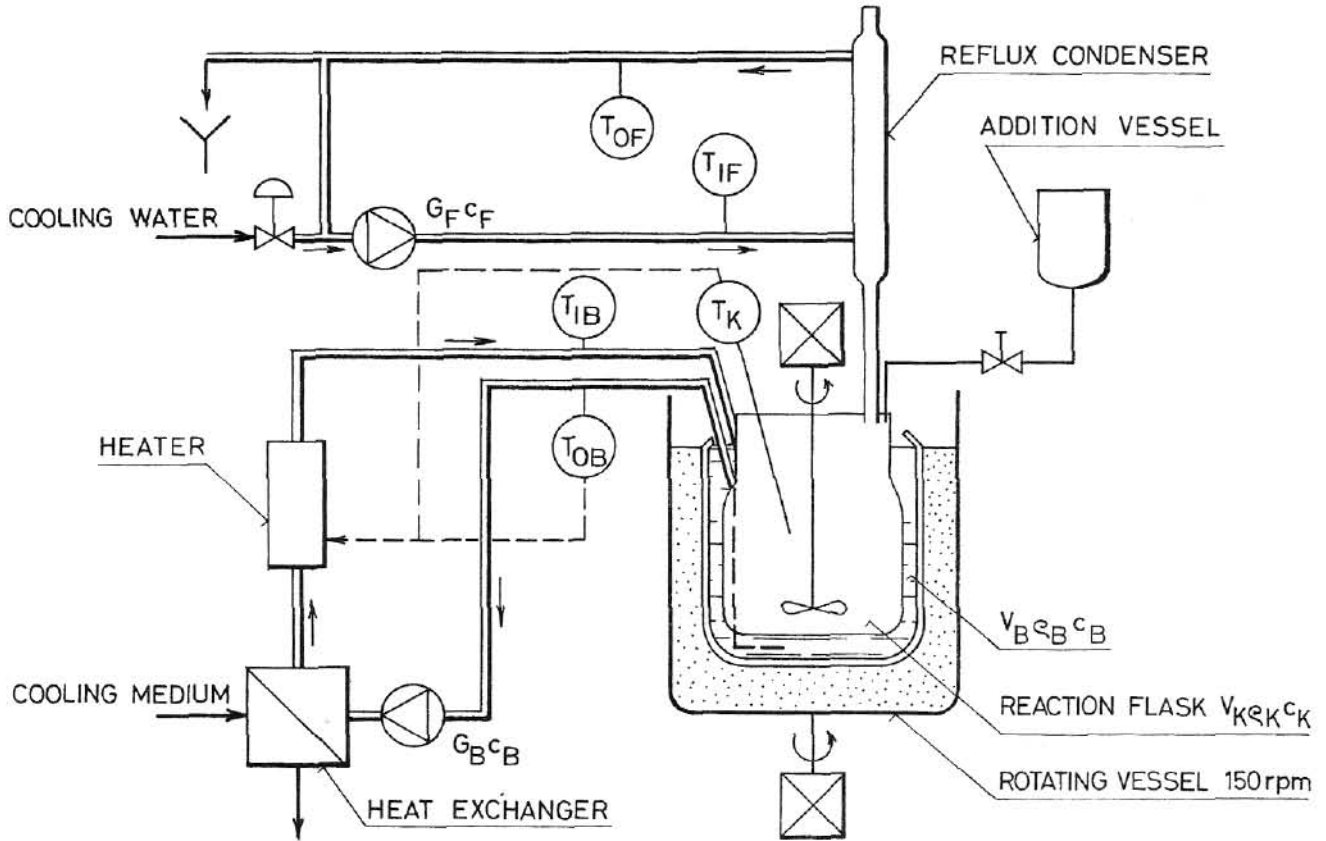


Figure 1: Reaction calorimeter

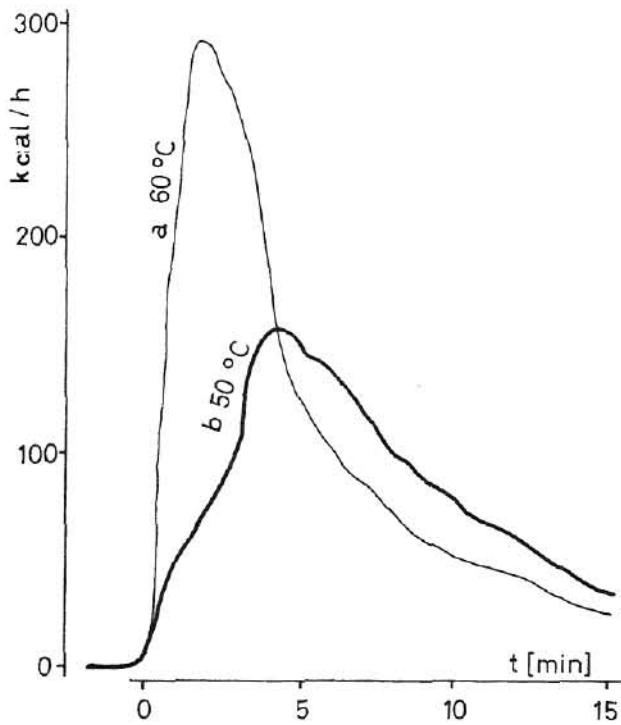


Figure 2: Thermokinetic profile

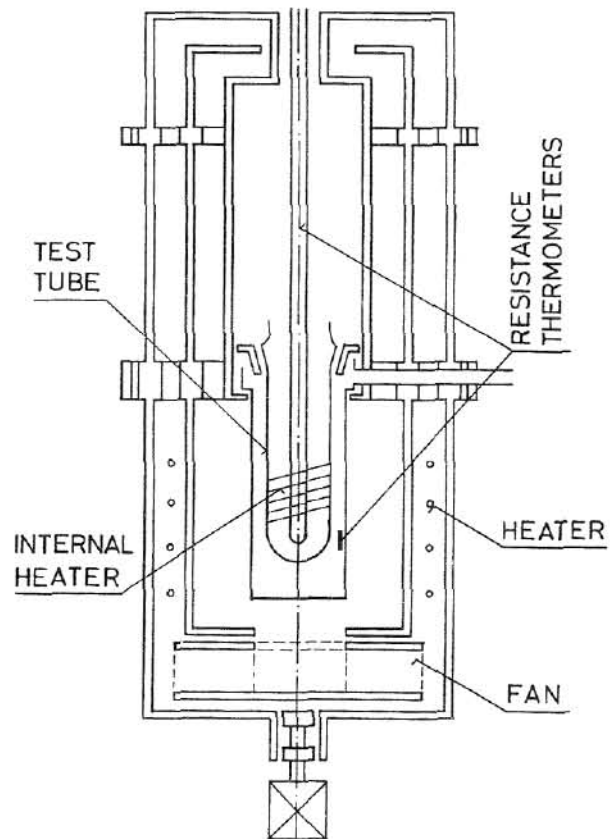


Figure 3: Safety calorimeter

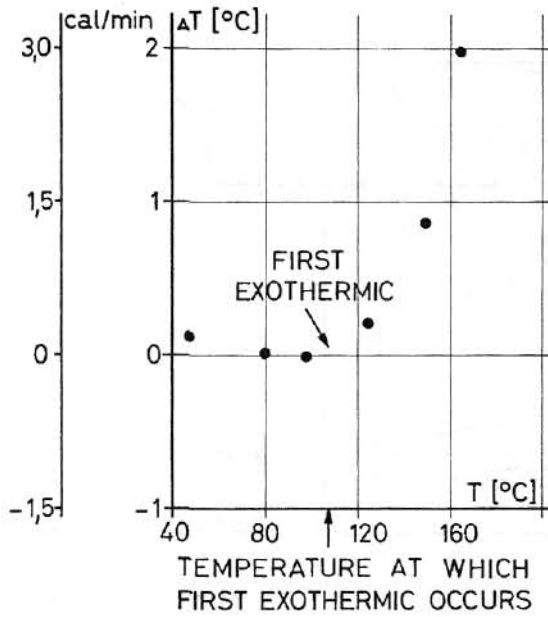


Figure 4: Temperature dependence of heat flux

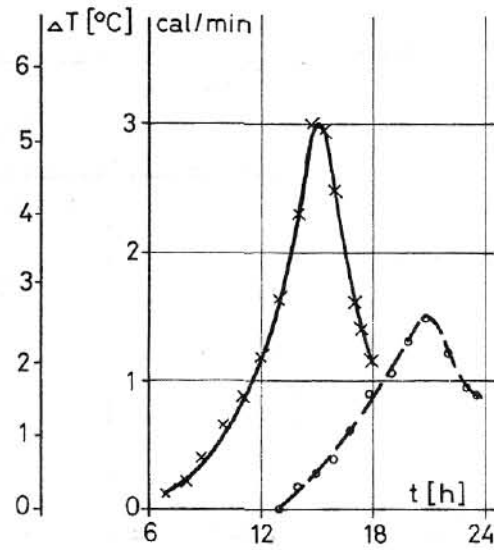


Figure 5: Comparison of heat release profiles

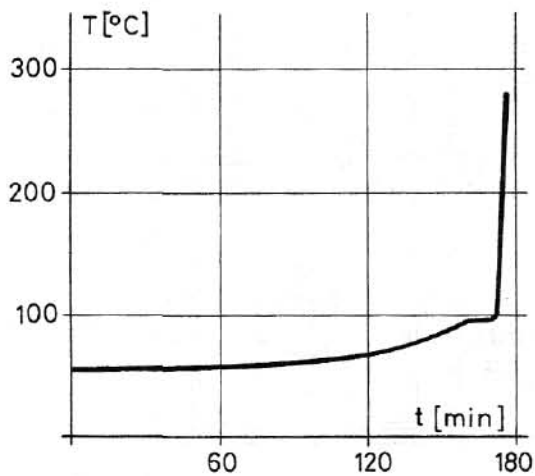


Figure 6: Temperature profile for adiabatic reaction