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The Development of Stirred-Tank Heat Flow Calorimetry as a Tool for Process Optimization and Process Safety[a])

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Abstract. Calorimetry based on the measurement of heat release rates has found widespread use in chemical process work, particularly for aspects of thermal process hazards. However, it has not yet found the breadth of application it deserves. This contribution discusses the tasks and problems of chemical process development and the role of heat flow calorimetry in this context. It reviews the historical development of heat flow calorimetry and analyzes the prerequisites for a successful development of the method in the future.

1. Stirred-Tank Heat Flow Calorimetry

Heat flow calorimeters measure the instantaneous rate of heat release (or heat consumption) at specified temperatures. *Fig. 1, a* shows the general scheme, *Fig. 1, b* the type where heat flow is controlled and measured by adjusting the temperature of a fluid in a jacket around the sample vessel.

Fig. 2 compares heat flow calorimetry with the better known heat accumulation calorimetry, where heat release causes temperature changes which are used to measure heat effects.

Stirred-tank heat flow calorimeters have all essential features of a laboratory reactor (and a few more). They are ideally suited to do experiments under the conditions of an industrial process and to determine in the course of such runs:

- rates of transformation (kinetics of reactions, crystallizations, *etc.*),
- heats of transformation.

Modern instruments provide a wide variety of operating conditions:

- temperature may be held constant, or may be increased or decreased at constant rate, or follow any imposed variation over time,
- pressure may be varied within limits restricted by the strength of the vessel,
- components may be added during measurement, in portions, at constant rate, or following a time program,
- stirring and mixing conditions may be varied.

2. Process Development and Its Problems

When we want to asses the role of heat flow calorimetry, we must have a look at chemical process development as a discipline, at its tasks, and at trends with respect to requirements and tools.

In the life cycle of a chemical product, the quality of process development affects

- the resource consumption to provide manufacturing facilities,
- the resources (raw materials, utilities, labour) consumed in its manufacturing,
- the emissions into the environment,
- the hazards caused by the process,

and thus has a great influence not only on economics but also on environmental and social acceptability.

A chemical process (*Fig. 3*) is a sequence of reaction steps and physical separation steps followed by 'finishing' (the elaboration of the final application form) designed to produce chemicals (such as drugs, crop-protection agents, coat-protecting additives, dyes or pigments) in a form (or formulation) which the consumer needs or particularly likes. It must be economic but also safe and ecologically acceptable.

The task of chemical process development is to elaborate such processes effectively and efficiently. Fast implementation of new processes is becoming increasingly important. Ideally, in a well-developed process, we have a basic understanding of all reaction steps (kinetics, influence of process parameters on selectivity, potential of thermally hazardous conditions) and a quantitative, model-based understanding of separation stages.

The tools of process development have improved in recent decades to an impressive extent. The most important of these tools are:

- methods of analysis to follow the composition of reaction mixtures and streams in separation processes,
- methods for physical property estimation,
- methods of steady state and dynamic process simulation.

Consequently, we might expect a similarly impressive improvement in process development effectiveness. Unfortunately, this has largely not happened. The state of the art is widely different between various process development groups. Some are indeed much faster and produce far better results than what was standard in-

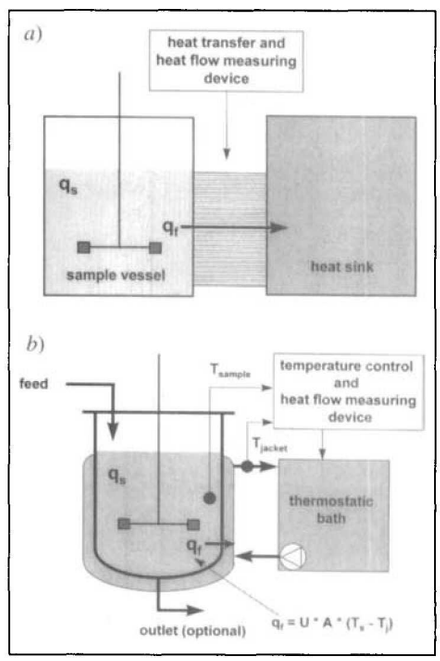

Fig. 1. *Stirred-tank heat flow calorimeter;* a) *general scheme;* b) *with control of jacket temperature*

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[a]) Extended version of a lecture given at the 8th *Mettler* RC User Forum in October 1996.

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dustry practice 20 years ago. Others have made little progress. The latter is particularly true for the interface of process engineering and project engineering (*i.e.*, the preparation of investment projects for new manufacturing facilities).

Likely causes of this situation are:

- The fact that sophisticated methods require highly skilled people who expect to work as creative and relatively independent partners in a team, combined with the fact that human communication skills have evolved much slower than technical skills.
- The appreciation and organizational attachment of process development as a discipline in the triangle research/engineering/manufacturing:
  - sometimes claimed as their domain by R+D directors with little affinity for process technology,
  - sometimes considered plainly superfluous by research chemists,
  - even with the organizationally most appropriate attachment (to 'manufacturing' or 'production and engineering'), process development remains a second-class activity, because short term tasks of high priority absorb most of the available management attention.

With the present trend to short term 'business focus', there is a lot of pressure to outsource the process engineering end of process development, making the communication problems even more serious than they were in the recent past. Consequently, in the real world, results of process development are often mere recipes and equipment specifications, which define operating procedures and process plants which work (in most cases), but miss the opportunity to provide the basic understanding required to assess the consequence of deviations from specified conditions, or to assure that the chosen conditions are really the best. Heat flow calorimetry is a tool which can help to narrow the gap between chemical research and process engineering. It could become even more important in this function in the future.

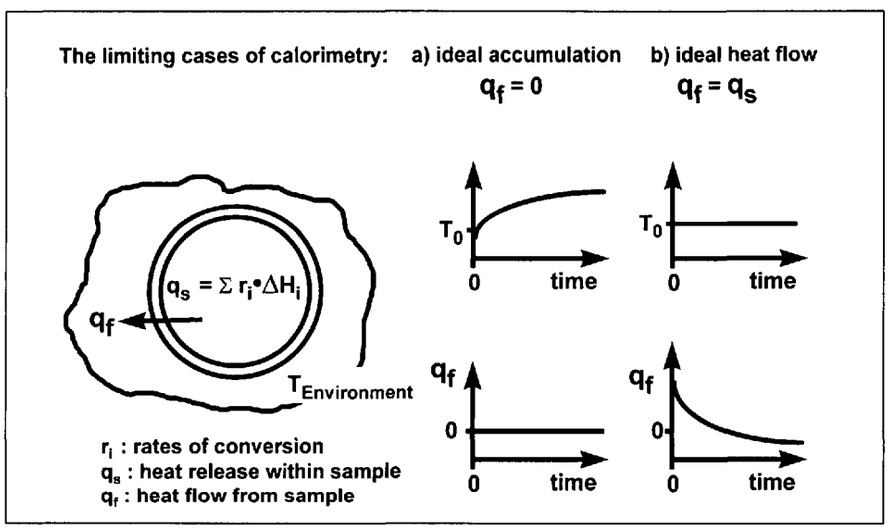

Fig. 2. *Comparison of heat flow calorimetry with heat accumulation calorimetry*

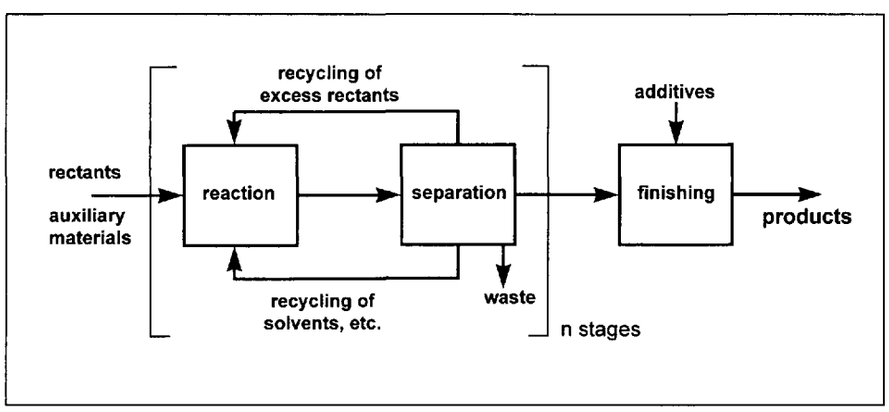

Fig. 3. *The chemical process*

3. Range of Applications

Stirred-tank heat flow calorimeters (the *Mettler* RC1 [1] being the best-known example) provide the following types of information:

- by direct measurement, the *instantaneous rate of heat release* (or consumption) $q(t)$;
- by integrating q over time, we obtain $Q(t)$, the *total heat* removed from (or absorbed by) the sample up to time t;
- if we can attribute this heat to a specific reaction, we obtain its *heat of reaction* $(-\Delta H) = Q(t)/n$ (n = moles converted at time t) and the instantaneous *reaction rate* $r(t) = q(t)/Q_e$ (Q_e = heat released for total conversion);
- the temperature difference between sample and wall to create a specified heat flux provides information about the *heat transfer properties* of the sample;
- the heat input (or removal) rate required to create a specified temperature ramp in the sample allows the calculation of the *heat capacity* of the sample and its *specific heat* c_p.

Such information has many applications, not confined to reactions. Heat release may mean very different things:

- a hazard,
- a chemical engineering problem (like design of heat transfer equipment, of matching heat release with available heat transfer capacity),
- an opportunity of tracing physicochemical transformations (reactions or phase transitions).

Applications dealing with the three mentioned aspects are now discussed.

3.1. *Thermal Process Safety*

Exothermic reactions may lead to runaway and thermal explosion, when the potential temperature rise is high and heat removal is insufficient, because reaction rate (and consequently heat release rate) increases very rapidly with increasing temperature, according to the *Arrhenius* equation $k(T) = k(T_0) \cdot \exp((E/R) \cdot (1/T_0 - 1/T))$ (with E = activation energy; R = gas constant)

The reason for high potential temperature rise may be:

- too high concentration of reactants of a highly exothermic desired reaction (this may happen in the batch, in the fed batch, or in the continuous mode);
- potential highly exothermic decomposition (mostly of reaction masses).

Moderate temperature excursions of

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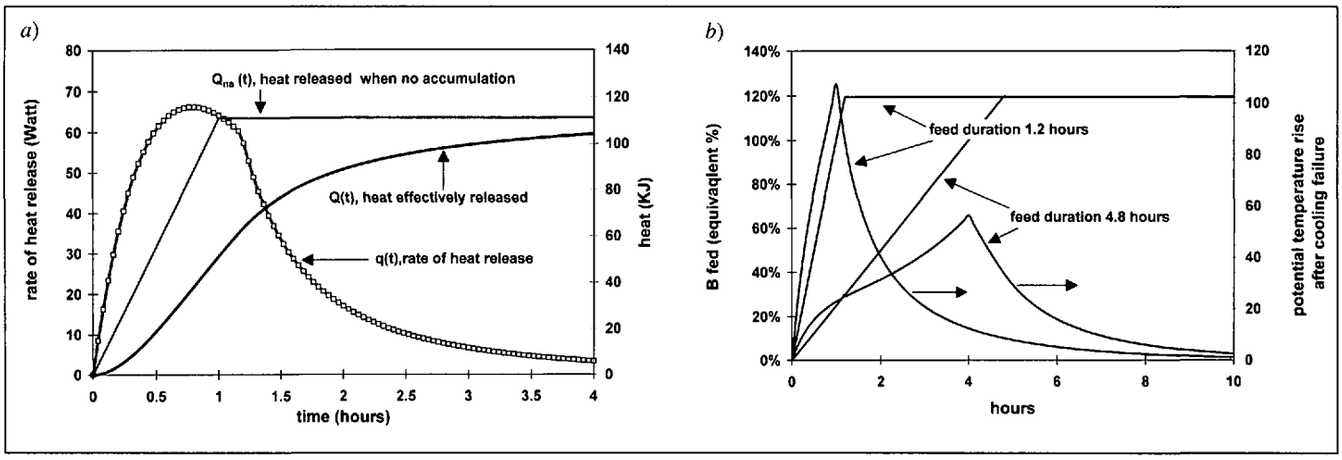

Fig. 4. *Determination of reactant accumulation in a fed batch reaction;* a) *heat flow and heat released;* b) *effect of feed rate on accumulation*

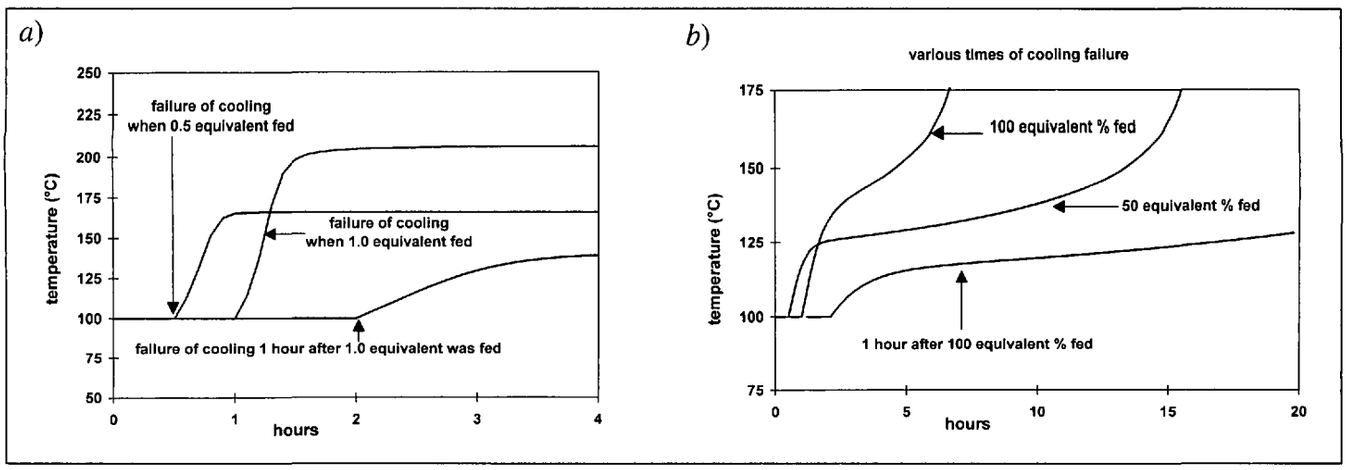

Fig. 5. *Cooling failure causing runaway;* a) *desired reaction as cause of runaway;* b) *desired synthesis reaction triggering decomposition*

desired reactions may trigger a decomposition runaway.

The analysis of the thermal safety of a process requires

- knowledge of the energies involved (heats of desired reactions and decomposition reactions) as well as specific heats to calculate the potential temperature rise;
- an assessment of the heat transfer capability of the industrial equipment;
- enough knowledge of kinetics to assess the extent of reactant accumulation;
- the assessment of runaway scenarios (preferably by simulation).

This approach of analysis was developed by many authors in recent years, particularly by *Gygax* [2], *Stoessel* [3], and *Steinbach* [4].

Stirred-tank heat flow calorimetry provides in this context

- heats of highly exothermic desired reactions (which are difficult to measure by heat accumulation calorimetry) and specific heats;
- heat transfer properties of the mixture under consideration;
- data on reactant accumulation;
- experimental confirmation of the initial phase of calculated runaway scenarios.

It is not suited for the investigation of slow, highly exothermic decomposition reactions. Here, micromethods (differential thermal analysis, differential scanning calorimetry) should be chosen. However, be aware: The necessary warnings on how *not* to evaluate kinetics of decomposition reactions would exceed the scope of this text!

Determination of reactant accumulation and adjustment of reactant addition, in such a way that the 'maximum temperature of the synthesis reaction' (MTSR) (attained by adiabatic conversion of accumulated reactants after a cooling failure) does not exceed a critical limit T_{max}, are the most important safety applications of stirred-tank heat flow calorimetry. *Fig. 4* shows how this is done for a fed batch reaction A + B → P; A is charged to the reactor (mostly diluted in a solvent). Its temperature is adjusted to the desired starting temperature of the process. Subsequently, B is fed at constant rate and the heat flow $q(t)$ is measured over time. At the end of the experiment, we have the following information:

- $Q(t)$, the amount of heat released in the experiment up to time t.
- Q_{total}, the amount of heat corresponding to the conversion of all A charged.
- $Q_{na}(t)$, the amount of heat which would be released up to time t, if the reaction would be very fast (no accumulation); it is proportional to the amount of B fed up to the equivalence point, and then equal to Q_{total}.
- $Q_{acc}(t) = Q_{na}(T) - Q(t)$, the amount of heat which can be released by the reaction mass when feeding is stopped at time t. For constant feed rate of B, Q_{acc} has its maximum at the equivalence point ($n_{A,fed} = n_{B,charged}$).
- Dividing Q_{acc} by the heat capacity (which increases with t as the batch mass increases), we obtain a worst-

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case estimate of the temperature rise which will occur when heat removal fails.

From *Fig. 4, b*, we see that (not surprisingly) for a second-order reaction, the feed duration must be increased by a factor 4 to halve accumulation.

Fig. 5, a shows calculated runaway scenarios, where the heat of the desired reaction causes the total temperature rise (cooling failure and stop of feed, after 0.5 and 1.0 equiv. of B are fed). *Fig. 5, b* shows the case, where the temperature rise caused by near adiabatic conversion of accumulated reactants of the desired reaction triggers an exothermic decomposition. Here, the heat from the desired reaction drives the temperature of the mass into a range where the decomposition reaction is fast enough to become dangerous. The main heat comes from the decomposition reaction.

For simulation, the following parameters were assumed (SR = synthesis reaction, D = decomposition):

- rate constants [h^{-1}] at 100° (process temperature): SR: $k \cdot c_{A0} = 1$; D: $k = 2.5 \cdot 10^{-4}$.
- Temperature rise for adiabatic conversion: SR: 200 K (80 K for *Fig. 5, b*); D: 500 K.
- Activation energy [kJ/mole]: SR: 60; D: 100.

When we detect unacceptable accumulation, we have to modify the process procedure, be it by elongation of the feed duration or by increasing the reaction temperature, or both. This often affects selectivity and, worse, product quality. This may lead to a whole new development effort. It is therefore advisable to consider the safety aspect mentioned above early in a process development project.

It has become a (questionable) custom to request a run in a heat flow calorimeter at the end of laboratory work before a new process procedure is introduced on industrial scale. This is a feasible way to avoid the worst. Early consideration of thermal effects and appropriate analysis of the situation would be more effective.

3.2. *Heat Transfer Issues*

Heat transfer is obviously an important function in chemical processes. We need data and understanding for

- safety analysis,
- optimization of process procedures,
- design of new equipment and assessment of existing equipment.

There is excellent literature on heat transfer mechanisms and heat transfer data. In most cases, no measurements are needed for solving heat transfer problems in process development. The fact is that we often ignore or neglect heat transfer issues. Thus, the main virtue of applying heat flow calorimetry is the fact that it creates awareness of heat transfer problems.

3.2.1. *Film Heat Transfer Coefficients of Process Fluids*

The film heat transfer coefficient at the boundary of a turbulent liquid is correlated by the *Nusselt* relation:

$$Nu\ (= h \cdot d_v/\lambda) = \text{const.} \cdot Re^{2/3} \cdot Pr^{1/3} \quad (1)$$

Nu = *Nusselt* number
Re = *Reynolds* number = $N \cdot d_s^2 \cdot \rho/\eta$
Pr = *Prandtl* number = $\eta \cdot c_p/\lambda$
h = film heat transfer coefficient [W/(m² · K)]
η = dynamic viscosity [Pa · s]
λ = thermal conductivity [W/(m · K)]
ρ = density [kg/m³]
N = stirrer speed [s⁻¹]
d_v = diameter of vessel [m]
d_s = diameter of stirrer [m]
c_p = specific heat [J/(kg · K)]

For pure liquids, reliable estimates of the film heat transfer coefficient are possible, based on data obtained from physical property estimation packages. For viscous slurries, this is not the case. Here, an experimental determination based on *Eqn. 1* is advisable. By rearranging it, we obtain

$$h = \underbrace{\text{const.} \cdot \frac{N^{2/3} \cdot d_s^{4/3}}{d_v \cdot g^{1/3}}}_{\text{engineering data of the reactor}} \cdot \underbrace{\sqrt[3]{\frac{\rho^2 \cdot \lambda^2 \cdot c_p \cdot g}{\eta}}}_{\text{physical properties of reactor contents}} = z \cdot \gamma \quad (2)$$

with g = gravitational acceleration [m/s²]

Here, h is the product of two factors, one of the depending only on equipment geometry and operation (the stirrer speed), the other only on physical properties of the sample.

In a stirred-tank heat flow calorimeter with heat flow control by wall-temperature adjustment (see *Sect. 4.1*), we determine the overall heat transfer coefficient (or its inverse, the overall heat transfer resistance) by measuring the temperature difference required to remove a known imposed heat release (electric heating) (*Fig. 6*). Since the heat transfer resistance of inner film, wall and outer film add

$$\frac{1}{U} = \underbrace{\frac{1}{h_s}}_{\text{depends on reaction mass}} + \underbrace{\frac{d_w}{\lambda} + \frac{1}{h_j}}_{\text{depends on reactor}} = \frac{1}{h_s} + \frac{1}{\varphi} \quad (3)$$

we can easily determine the sample film coefficient. This is preferably done by means of the *Wilson* plot [5][6] (*Fig. 7*): We vary the stirrer speed N and plot the inverse of the overall heat transfer coefficient U over $N^{-2/3}$, first with a liquid of known γ to determine the heat transfer data of wall and outer film, $1/\varphi$, and the geometric factor z of the calorimeter vessel, then with the sample to determine its γ-value. The same procedure can be applied to determine φ and z of industrial vessels, if they are equipped with a variable speed stirrer drive.

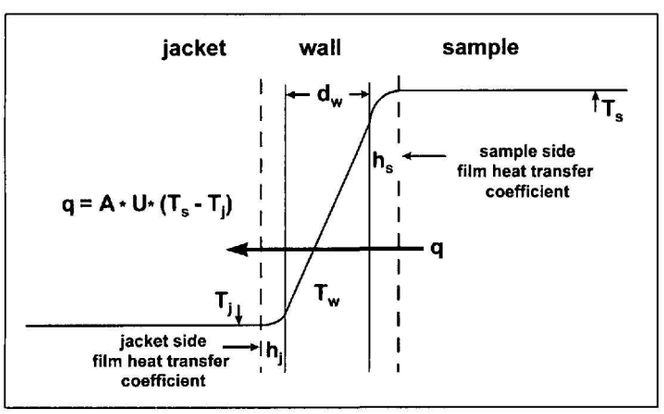

Fig. 6. *Heat transfer through wall of stirred vessel*

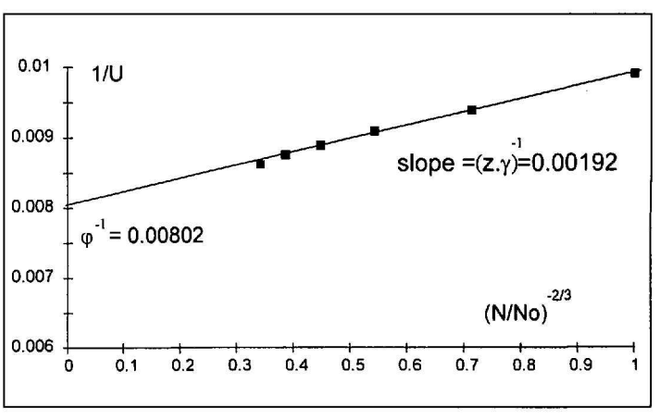

Fig. 7. Wilson *plot* (Courtesy of *F. Stoessel*)

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3.2.2. *Design of New and Assessment of Existing Equipment*

The use of heat transfer data in the design of new equipment is straightforward: Know the heat duty and the available (or allowable) temperature of the heat transfer fluid: calculate the required heat transfer area. Less obvious and rarely applied is the critical assessment of existing equipment. Often, we experience long duration of process phases associated with heat transfer and mostly attribute the cause to high heat of reaction, *etc.*, whereas the real cause is poor design or operation of the equipment (circulation of the heat transfer fluid, stirring of the process fluid). When we know the heats to be transferred and the heat transfer capacities achievable by correct design and operation, it is often easy to make the necessary corrections.

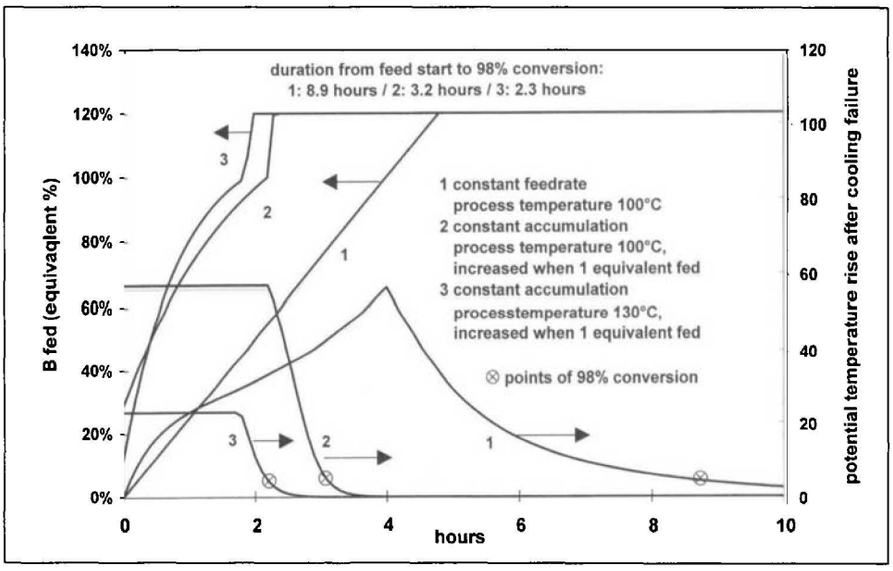

Fig. 8. *Optimization of feed rate and temperature*

3.2.3. *Scale-Down for Scaleup*

On laboratory scale, heat effects cause rarely problems; mostly they are not noticed; consequently most laboratory procedures are elaborated as if heat effects would not exist. The problems start with scaleup: Feed rates prescribed cannot be maintained, because heat cannot be removed fast enough or because they would lead to unacceptable reactant accu mulation. Therefore, as mentioned before, heat removal considerations should start early in process development work, and the timing of the elaborated process steps should be feasible on an industrial scale.

The correct sequence of actions is:

- determine heats of reaction, heats of vaporization, heat capacities, *etc.*;
- estimate the heat transfer capacity of industrial equipment intended to be used;
- estimate the required heat transfer times for heating, cooling, evaporation, reactions, *etc.*;
- do the laboratory experiments (at least the final ones) with a duration of the process steps which is in line with the industrial process.

3.2.4. *Cycle Time Optimization*

'Debottlenecking' (capacity increase of existing plants without major investment) has become an important process development activity in recent years. In a batch plant, capacity is determined by the expression (plant availability (also called on-stream efficiency) · batch yield/cycle time). The component which can be most easily improved is cycle time. There are three main types of process activity requiring time:

- macro mass transfer (charging/discharging),
- reaction to the desired degree of conversion,
- heat transfer (heating, cooling, heat transfer for physicochemical transformations like reaction, vaporization, *etc.*).

Very often, heat transfer is the most time-consuming among these activities, and when we know the heat to be transferred and the (correct) heat transfer capacities of the equipment, we are well-supported in finding ways to improve.

If in reaction steps heat removal is limiting (this is the case for fast and highly exothermic reactions), constant addition rate of reactants (a standard procedure in batch processing) is correct. If, however, the need to limit accumulation restricts the allowable feed rate, addition programs providing constant accumulation should be applied. From *Fig. 8* (simulated with the same reaction parameters as *Fig. 4, b*), we see that feed duration can be about halved by this measure (left side part of curve 2). If we allow the process temperature to rise as accumulation decreases (due to the completion of the reaction after the end of the feed period), the time to achieve a desired extent of reaction (*e.g.* 98%) can be considerably reduced (right side part of curve 2).

If temperature excursion considerations are the only restriction on process temperature, cycle time can be further reduced by optimization of the process temperature during the feed phase:

The higher we choose the temperature, the less accumulation we can tolerate. On the other hand, higher temperature will increase the reaction rate constant. Reaction rate is proportional to the product 'concentration of the fed reactant times $k(T)$' or:
$((T_{max} - T) \cdot k_{\infty} \cdot \exp(-E/RT))$. By differentiation of this rate term with respect to T, we obtain

$$T_{opt} = T_{max} - R \cdot T_{opt}^2/E \qquad (4)$$

There is no need of solving the quadratic equation for T_{opt}, as $T_{opt} = T_{max} - R \cdot T_{max}^2/E$ is a good conservative approximation. The rate optimum is flat (the gain in cycle time by increased temperature is modest) and, for the sake of safety, temperatures below T_{opt} should be chosen anyway. For curve 3 in *Fig. 8*, T was chosen according to this optimization.

3.3. *Heat Effects as an Event Tracer*

This is the most valuable and probably the most neglected use of heat flow calorimetry. When we trace heat release (or absorption), we get immediate information of what is going on in a reactor. Some examples:

- Catalysis and inhibition (*Fig. 9, a*, left): The effect of added components is immediately seen.
- Reaction progress affecting kinetics due to polarity changes (*Fig. 9, a*, right): The reaction shown is a first-order isomerization. As conversion proceeds, polarity of the medium increases, enhancing the rate constant by a factor of *ca.* 30.
- Initiation of reactions with a tendency to hazardous reactant accumulation (*Fig. 9, b*): If we can immediately see, whether the formation of a *Grignard* reagent 'starts' (left part of *Fig. 9, b*), it is easy to elaborate a procedure which safely avoids accumulation.

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- Sudden changes in reaction rates (*Fig. 9, c*): In the liquid-phase oxidation of aromatic methyl groups with molecular oxygen, catalyzed by Co and Br, rate changes by orders of magnitude can be observed.

Although it is rarely possible to establish accurate and reliable kinetics from heat flow experiments alone, heat flow information considerably accelerates the acquisition of kinetic understanding. Also, we will take samples for component analysis much more selectively and consequently save cost and move faster.

3.4. *Limitations of the Method*

Heat flow calorimetry is, of course, not 'a cure to all evils'. Many failures experienced with the method are due to attempts to apply it where it is inappropriate. A few examples:

- Kinetics of complex reactions, without the support of supplementary methods.

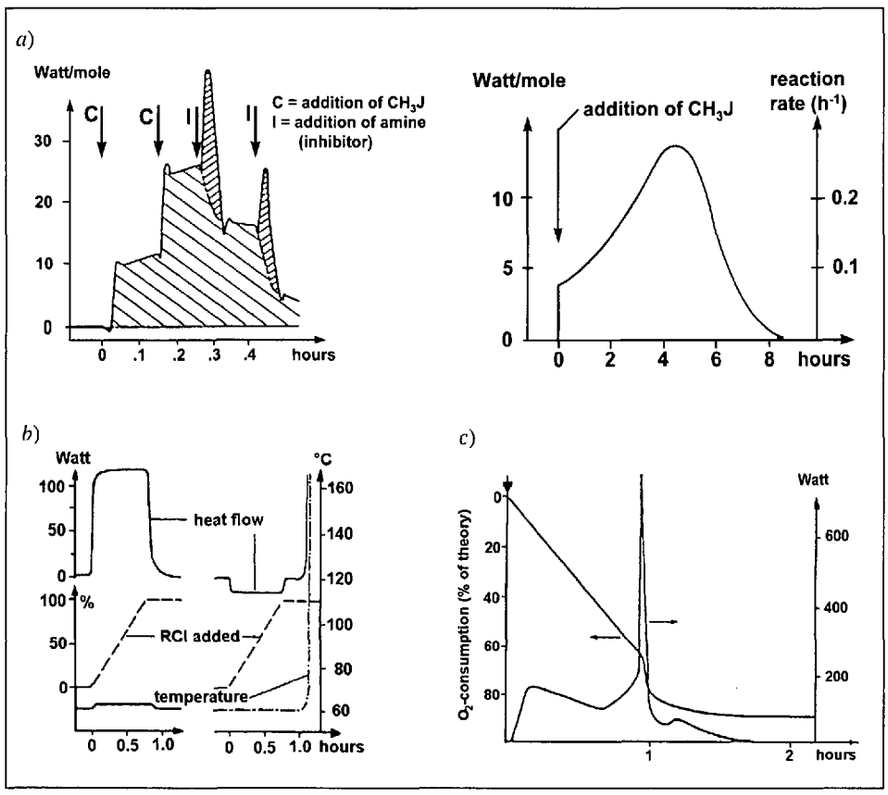

Fig. 9. *Heat release as a tracer:* a) *The highly exothermic isomerization of trimethyl phosphite* [7]. Catalysis and inhibition (catalyst: CH_3I; inhibitor: amine). *Acceleration of reaction rate, caused by increasing polarity of the reaction mixture.* b) *The check of the reaction initiation in an industrial manufacture of* Grignard *Reagent* (RCl + Mg → RMgCl); c) *The oxidation of chlorotoluene in solution with molecular O_2, catalyzed by Co^{2+} and Br^-* [8] ($R-CH_3$ → R–CHO → R–COOH)

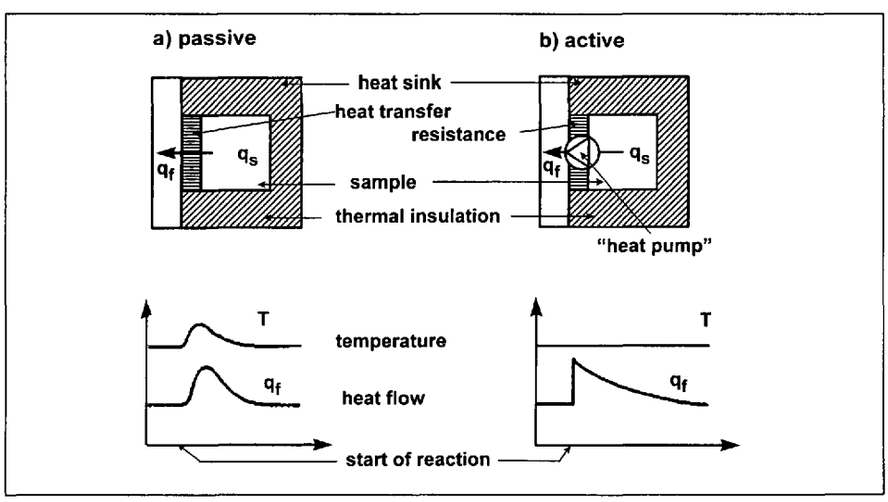

Fig. 10. *Passive and active heat flow calorimeters*

Even for simple reactions, there are problems (*e.g.* the determination of the exact reaction order). Be aware of the fact that the rate of a stoichiometric second-order batch reaction at 90% conversion is 1% of its initial rate. Consequently, it is impossible to get any meaningful information from heat release at high conversion.

- Investigation of slow, very exothermic decomposition reactions (as mentioned above).
- Working under reflux conditions.
  It is possible to include a reflux condensor in the overall heat balance. Appropriate equipment is available. However, the loss of accuracy and, worse, reliability is considerable. Working under reflux is a standard mode of laboratory operation, because it is an easy way of maintaining a temperature accurately. Doing the same on an industrial scale is in most cases a waste of energy. Very few processes require reflux (*e.g.* for the stripping of a reaction product in an equilibrium reaction to obtain high conversion, or for the stripping of components which are detrimental for the reaction or for the desired product). Therefore, reflux on plant scale should be confined to such cases and to process steps where heat has to be removed from the reactor (because reflux is a very effective and reliable way of heat removal). On a laboratory scale, heat should be removed through the wall. It will then be measured much more accurately (provided evaporation is suppressed by applying pressure).

4. Instrumentation

4.1. *Available Calorimetric Principles, Classification of Calorimetric Instruments*

There is no generally satisfactory classification of calorimeters, because there are so many characteristic features. With focus on heat flow calorimetry, the following classification (*Figs. 2* and *10*) has been proposed [9], distinguishing mainly between:

- heat accumulation methods (adiabatic and most isoperibol instruments),
- heat flow methods.

Heat flow methods may be further classified with respect to their various ways of:

a) Heat flow control:
- passive (heat flow driven by partial heat accumulation, *Fig. 10, a*),
- active (heat flow forced by a control

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system, *Figs. 10, b* and *11*), *e.g.*
- compensation heating,
- *Peltier* heat transfer,
- temperature adjustment in the 'heat sink'.

b) Heat flow measurement:
- electric current (*Peltier* or *Joule* effect),
- heat balance in the heat sink,
- temperature difference over heat transfer resistance.

Some Comments:
- **Passive heat flow calorimeters** are useful only for small samples and good heat transfer between reactor and heat sink. If this condition is not fulfilled, dynamics will be poor and deviations of the reactor temperature from the desired value will be large.
- ***Peltier*** heat transfer (*Fig. 11, a*) is based on a principle which might be called the inverse of the effect on which the thermocouple is based: When we impose a current on a thermocouple, heat will be transferred from junction to junction. *Peltier* cells are batteries of large numbers of semiconductor 'thermocouples'. Heat flow is strictly proportional to current; thus, *Peltier* cells can be used simultaneously as heat pumps and heat flow measuring devices. (A complication comes from the fact that a *Peltier* battery has its own heat generation, caused by *Ohm*-type losses which are proportional to the square of the imposed current.) *Peltier*-type heat flow calorimeters have excellent dynamics. However, until recently, there were serious restrictions in their application range (temperature range, materials, and geometry of reactor).
- For **compensation heating** (*Fig. 11, b*), a constant temperature difference is maintained between the sample and the heat sink. This causes a constant heat flow out of the sample (constant as long as the heat transfer resistance is constant). The temperature of the sample is maintained by means of an electric heater with measured power input. Heat release rates in the sample cause corresponding changes of the power input to the heater. Among active heat flow calorimeters, compensation heater types are by far the easiest to build. They also have excellent dynamics. Their problem is the fact, that changes of the heat transfer resistance (which are unfortunately quite common when reactions take place) cause serious baseline drift.
- Heat flow calorimeters **adjusting the temperature of the heat sink** (jacket around or coil within the sample) for heat flow control (Fig. *11, c* and *d*) are presently most commonly used for process work. Heat flow is measured by one of two methods:
  - by sensing the temperature difference over the heat transfer resistance (*Fig. 11, c*). Here, variation of the heat transfer resistance affects sensitivity (with other words: the calibration factor).
  - *Via* a heat balance on the heat transfer fluid (*Fig. 11, d*). Here, dynamics are poor, if the mass of heat transfer fluid within the heat balance limits cannot be kept very small.

Both subtypes are calibrated by means of an electric heater immersed in the sample.

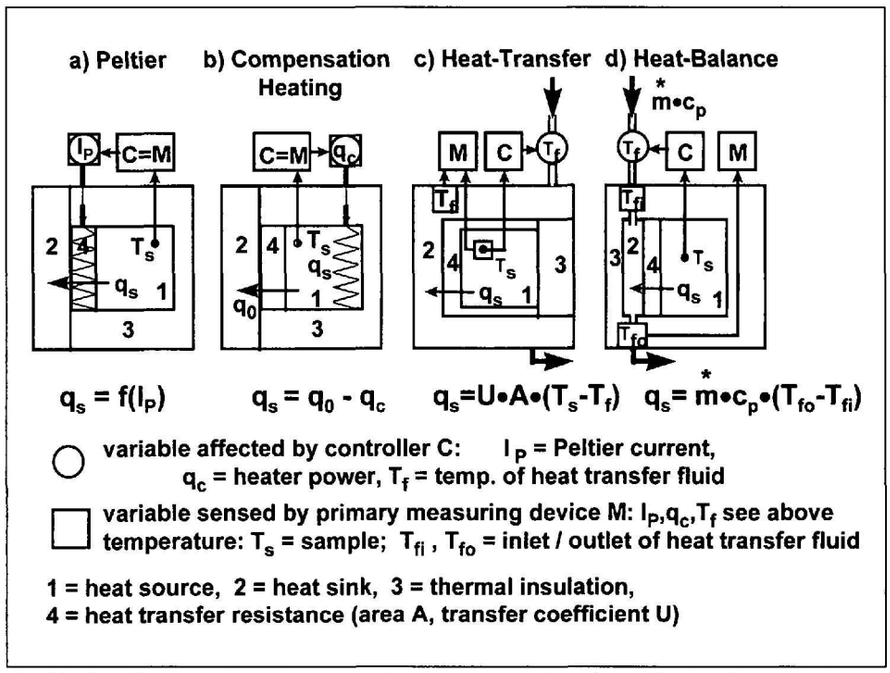

Fig. 11. *Combinations of heat flow control and measurement used in active heat flow calorimeters* (from [38])

Table 1. *Heat Flow Calorimetry*

1923	*Tian* [10]	thermopile calorimeter
1948	*Calvet* [11]	twin-cell thermopile calorimeter
1965	*Becker* and *Walisch* [12]	*Peltier*-controlled heat flow calorimeter
1960–83	various authors in industry	heat flow calorimeters for safety and process design
1982	*Nilsson* and *Silvegren* [13]	model-supported *Peltier*-controlled heat flow calorimeter
1991	*Eigenberger* and coworkers [15]	laboratory fermenter calorimeter
1992	*Moritz* and coworkers [17]	model-supported compensation-heater heat flow calorimeter
1993	*Reichert* and coworkers [18]	calorimetry with a model-supported standard laboratory reactor
1982/97	*von Stockar* and coworkers [19][20]	BSC-81/RC1-based fermentation calorimeter

4.2. *Short History of Heat Flow Calorimetry and Overview of Past and Present Designs*

Heat flow calorimetry (*Table 1*) has its roots in differential thermal analysis. It was systematically developed in the second quarter of this century by *Tian* [10] and *Calvet* [11], who designed highly sensitive unstirred instruments which are still

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in use. Important systematic work towards modern active heat flow calorimetry was done in the sixties by *Becker* and coworkers [12] in Germany (Universities of Saarbrücken and Frankfurt).

Other stirred-tank heat flow calorimeters developed at universities are:

- The *Peltier*-type instrument by *Silvegren* and coworkers [13] (now available commercially by *Chemisens* [14]).
- A fermenter calorimeter from the University of Stuttgart [15], also available commercially (by *Berghof* [16]).
- Model-based designs by *Moritz* and coworkers [17] and *Reichert* and coworkers [18]. They will be discussed in the section on future development.
- Adaptations of BSC-81 (*Ciba*) and RC1 (*Mettler*) instruments for the use in fermentation by *von Stockar* and coworkers [19]. The most recent designs are sensitive enough (< 50mW/l) to trace oscillations of heat release rate which are caused by synchronization of cell growth [20].

Stirred-tank heat flow calorimeters designed for industrial needs were built in almost every major chemical company (*Table 2*).

Table 2. *Heat Flow Calorimeters from the Chemical Industry*

Year	Type	Author	Affiliation
1957	heat flow calorimetry on an industrial reactor	*Morgan* [21]	*Phillips Petroleum*
1960	passive 'Thermokinegraph'	*Baumgartner* and *Duhaut* [22]	Inst. Français du Pétrole
1966	active compensation heater	*Andersen* [23]	*Monsanto*
1966/81	active adjustment of jacket temp.	*Regenass* and coworkers [24–27]	*Ciba* CH
1969	active adjustment of jacket temp.	*Meeks* [28]	*Dow*
1973	active compensation heater	*Köhler et al.* [29]	*BASF*
1975	active adjustment of jacket temp.	*Hub* [30][31]	*Sandoz*
1976	active compensation heater	*Chandler* [32]	*Ciba* UK
1977	active wall compensation heater	*Schildknecht* [33]	*Roche*
1979	active compensation heater	*Hentschel* [34]	*Hüls*
1980/83	active compensation heater + heat balance on jacket	*Litz* [35]	*Bayer*

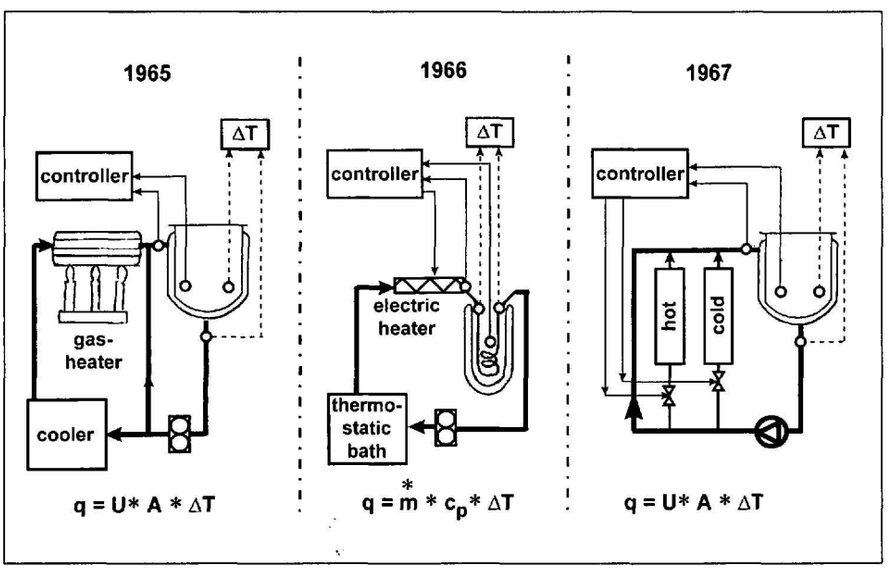

Fig. 12. *Early heat flow calorimeters at* Ciba

The first design to be mentioned here is not an instrument but an analogue computer (with vacuum tubes). Its purpose was the control of feed rate and cooling of an olefin polymerization reactor at *Phillips Petroleum* based on the use of heat release to calculate the instantaneous reaction rate and the degree of polymerization (*Morgan* [21]). This was a very progressive approach. Nothing on its implementation, not even recently, was found in the literature search.

The first instrument from industry found in this search came from the Institut Français du Pétrole [22]. It was a passive heat flow calorimeter which was available commercially in the early sixties, but seems to have disappeared soon thereafter.

The most frequently used method of heat flow control is compensation heating (used by authors from *Monsanto* (*Andersen* [23]), *BASF* (*Köhler* [29]), *Ciba* UK (*Chandler* [32]), *Roche* (*Schildknecht* [33]), *Hüls* (*Hentschel* [34]), and *Bayer* (*Litz* [35]), sometimes with sophisticated features to cope with the inherent flaws of this method.

Adjustment of the temperature of a heat exchanger coil (and heat balance over this coil) was used at *Dow* (*Meeks* [28]).

Jacket temperature adjustment was used at *Ciba* Basel (*Regenass* [24–26], *Giger* [27]) (deriving heat flow from the temperature difference over the reactor wall) and at *Sandoz* (*Hub* [30][31]) (determining heat flow by a heat balance on the jacket). The *Sandoz* design was commercialized by *Contraves*, the *Ciba* design by *Mettler* [1].

The list is necessarily incomplete. Many successful efforts were probably never published. That is the reason of the mention of the work by Dr. *Chandler* who built with essentially no money a compensation heater calorimeter which worked perfectly in its range of application.

Reviews on heat flow calorimetry were given by *Becker* [36], *Regenass* [37][38], *Karlsen* and *Villadsen* [39], and *Moritz* [40].

4.3. *The Development within* Ciba

Calorimetric work in the Chemical Engineering Section of *Ciba* started 1965 with the task to keep a *Skraup* reaction (the highly exothermic formation of a quinoline by condensing an aniline with glycerol in sulfuric acid) under control. There had been a runaway in the plant, and process safety had to be improved [41]. At that time (*Fig. 12*), temperature control on industrial

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stirred tanks was improved by 'cascaded control': The heat flow from or to the reactor (steam/cooling water) is controlled not only by the temperature of the reactor contents, but the temperature of the jacket is also sensed and adjusted according to the deviation of the reactor temperature from its set point: *e.g.*, when T_R is 1° too high, the jacket is set 5° below the reactor temperature set point. This greatly improves temperature control stability.

A little box built at *Ciba*'s electronic shop [42] made this type of temperature control available for the laboratory. Plotting the temperatures of reactor and jacket *vs.* time (on an automatic recorder), we obtained heat release data which immediately led us to a kinetic model of the reaction, from which we could predict safe and time-efficient temperature programs for the industrial reactor. This fascinated us and gave us recognition and freedom to do some method developments.

When we want to measure heat release rates by transferring the involved heat to a heat transfer fluid, the temperature of this fluid must be adjusted very fast (at least, we thought so at the time).

Our first attempt (*Fig. 12*, left) was a jacket circuit with cooler and a gas heater switched on and off by a controller. Heat release rate was determined from the temperature difference between reactor and jacket. It worked, but it was an energy-wasting machine, and the big fire was not exactly what we needed in the lab.

Next (1966), we tried a fast temperature-controlled electric heater on a coil circuit in a *Dewar* type of reactor (*Fig. 12*, middle). We used constant fluid flow and measured the temperature between the inlet and outlet of the reactor. The result was a typical lab calorimeter, useful for data, but awkward to operate.

Third (1967), we went back to jacket temperature control (*Fig. 12*, right), now with temperature adjustment by mixing (injection of precooled or preheated fluid [43]),

With this design, we could solve many process problems. By 1970, this type of instrument was used on a service basis for customers in various areas of *Ciba*. The key players in the early period were *H. Martin*, who developed the method as a service, and *J.R. Randegger*, who managed the group for some years and then introduced the method to US sites of *Ciba* [44]. Three application examples from this time period were shown in *Fig. 9*.

Besides applications, we could also look into the basics. Several colleagues did their Ph.D. thesis work on performance evaluation and on applications of the *Ciba* heat flow calorimeters (*Martin* [7], *Gautschi* [45], *Kanert* [46], *Bürli* [47], *Beyrich* [8]).

In the early seventies, we came to the conclusion that we should have 'Bench Scale Calorimeters' (BSC's) (*Fig. 13*) in the various process development departments, for two reasons:

- After a few serious thermal runaways in the plants, there was a long queue of work orders.
- We had noticed that is was very difficult to convey insight on process improvement opportunities to those responsible for the processes.

After a failed attempt to convince an established supplier of thermal instruments to provide calorimeters for us, we started a redesign. It was fortunate that *W. Kanert*, a chemist with a professional education as a draftsman, had just obtained his chemistry diploma and was looking for a Ph.D. thesis opportunity. He implemented the 'BSC-75' [26][46], a design which was much more compact than its predecessor (*Fig. 13*). 18 units were built; some are still in use. A wide range of options were available:

- pressure reactors up to 150 bar,
- heaters, coolers, and heat transfer fluids for a temperature range of –70 to 250°,
- various construction materials for reactors (glass, glass-lined steel, titanium).

In 1979, we were faced with problems of instrument supply again. We improved the mechanical design (based on studies done jointly with *Mettler*) and used a computer-based control system supplied by the same manufacturer [48] who had supplied the electronic equipment of the BSC-75.

This 'BSC-81' [27] could be accommodated in a standard fume cupboard and could do automatic experiments, data acquisition, and evaluation. However, it was far less successful than the BSC-75 as it required 'experts' to operate it, and there were more computer failures than acceptable for a safety calorimeter.

In 1981, the project of a *Mettler* Bench Reaction Calorimeter was started. The 'RC1' became commercially available in 1985, first mechanically identical with the later version of the BSC-81, but with an appropriate and reliable control and evaluation system; however, with quite restricted application accessories. Only recently, important features of our BSC-75 (pressure, temperature range) were added to the RC1.

Fig. 14, a–c, shows photographs of *Ciba* instruments from various periods.

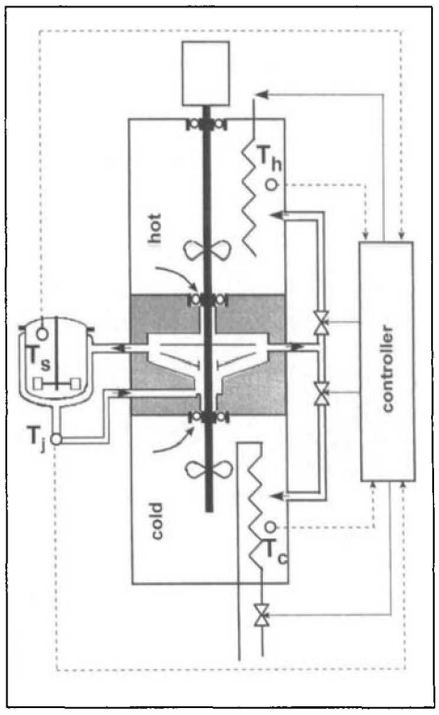

Fig. 13. *BSC-75*

5. Future Developments

5.1. *How Well is Heat Flow Calorimetry Developed?*

At present, heat flow calorimetry is generally accepted as a tool for optimizing processes and assuring process safety. Several designs are available commercially. Many users build their own instruments from components now easily available (fast, closed thermostatic baths, control hardware and software). Thus, one might call heat flow calorimetry a successful method. However, if we compare heat flow calorimetry with other scientific methods and measure its success by the percentage of the area of its potential application it occupies and by the speed of its development, then heat flow calorimetry is at the low end of the success ladder.

Some methods found general acceptance immediately after their detection. The most stunning example is X-rays (more than 1000 publications in the first year [49]). Methods introduced extremely successfully in the recent past are Atomic Force Microscopy [50] and the Polymerase Chain Reaction [51]. Other methods fully developed within a few decades (*e.g.* GLC and NMR).

On the other hand, Liquid Chromatography (*Table 3*) developed extremely slowly. It became widely used as an analytical tool only recently in the form of HPLC (High-Pressure or 'High-Performance' Liquid Chromatography).

In stirred-tank heat flow calorimetry, a few hundred instruments are in use in

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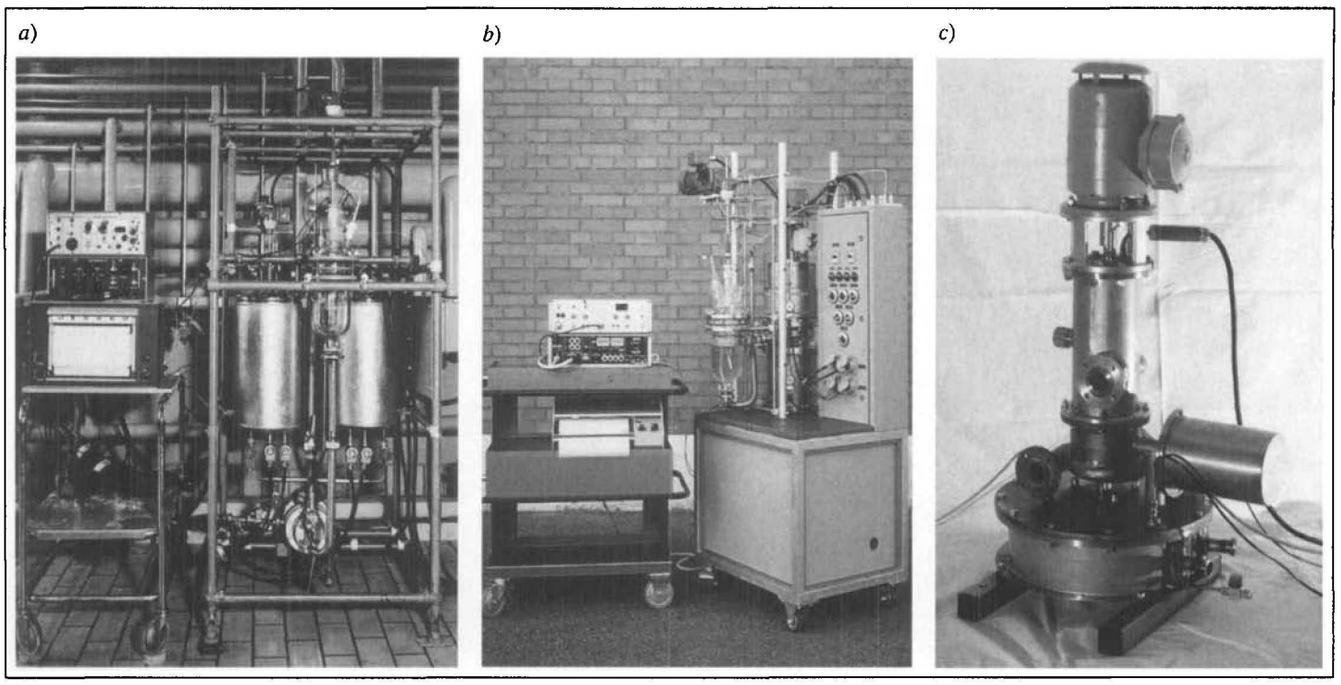

Fig. 14. *Photographic documentation of the effort for more compact design:* a) *the voluminous setup in the late sixties,* b) *the BSC-75,* c) *the 'heart' of the BSC-81*

Table 3. *Liquid Chromatography* [52]

1906	*Tswett* (botanist)	separation of components by adsorption chromatography
1913	*Willstätter*	cannot reproduce *Tswett*'s results and condemns the method
1931	*R. Kuhn*	recommends the method
1939	*Schraiber*	discovers thin-layer chromatography his work remains unnoticed
1941	*A.J.P. Martin* and *R.L.M. Synge* (biologists)	introduce partition chromatography develop plate theory and elution theory suggest high-pressure LC (HPLC) suggest gas chromatography
1951	*Kirchner*	rediscovers thin-layer chromatography
1968	*J.J. Kirkland*	UV detector for LC
1970s		HPLC becomes an established analytical method
1990s		HPLC is one of the most used analytical methods

quite restricted areas of application. The extent of use is summarized and commented in *Table 4*.

The development of a method is driven by needs and its capabilities to serve the needs, and by human fascination and enthusiasm (*Table 5*).

Heat flow calorimetry has the problem that it has no glamour and is not in the mainstream interest of potential users, not among physical chemists, much less among chemists. The interest of chemical engineers is also low, although increasing. Further constraint results from the fact that present instruments are either too costly and require too much space, or they are not easy enough to use to be a real help in problem solving. Consequently, there is not much demand, and no instrument maker will dare to put much resources into the development of a more suitable instrument.

5.2. *Needs and Open Opportunities*

Heat flow calorimetry could be as much a standard method of monitoring reactions as all the forms of spectrometry and chromatography presently in use. It is not as specific as the methods mentioned, but much more convenient.

When we try to translate the needs of the users into instrument specifications such as:

- measuring qualities (sensitive, accurate, representative of process under question),
- handling qualities,
  - variety of standard operations (stirring, adding components, ramping temperatures, *etc.*),
  - time requirement for preparation, for the calorimetric run and for the evaluation,
  - space requirement in the laboratory,
- availability to user (cost of acquisition and cost operation),

we see that the problem of presently available calorimeters is not with sensitivity or with accuracy, but with handling properties and with cost.

The handling and cost specifications are set by conventional laboratory reactor systems (*i.e.*, vessels for samples (reaction mass), heat transfer equipment, control equipment, *etc.*). Such systems are of course not calorimeters, but they have many components in common with calorimeters, including computers for data acquisition and/or automatic running procedures.

This leads to the question, whether it is feasible to turn conventional laboratory equipment into a simple calorimeter by modeling and data treatment, and if so, what accuracy and sensitivity of heat release should one aim for?

- An *accuracy* of ± 10% of the released heat is probably sufficient and easily achievable.
- *Sensitivity* requirements are more stringent and much more difficult to achieve. Probably, the detection of a change in heat release rate (in a 5-min mean), which corresponds to 5% of the maximum heat release rate of the investigated reaction, would be quite helpful. But if the maximum is 20 W/l, this

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means that a change in heat release of 1 W/l should produce a meaningful signal. This is not an easy task.
- Good *dynamics* are also of interest. We often want to know, whether a reaction starts immediately when the reactants get together, or whether there is a delay.

In the past, much effort was made to match heat release with heat flow as accurately and as fast as possible by means of sophisticated control hardware. The advent of fast and inexpensive computers provides opportunities to reconstruct true heat release rates from signals which are badly distorted. This greatly reduces performance requirements on instrument hardware: heat flow calorimeters can be made simpler and cheaper.

Two attempts in this direction have been published in recent years:
- A model-based isoperibol calorimeter developed by *Moritz* and coworkers [17], which operates similar to a traditional combustion calorimeter (using a large liquid mass as thermal ballast to keep temperature changes in the sample small) and calculates instantaneous heat release rates. Published performance data are impressive. The approach relates to earlier work by *Küssner* [53].
- *Reichert* and coworkers [18] attached a fast commercial thermostat to a commercial autoclave and modulated the set temperature of the reactor within narrow limits. They obtained (for a slow polymerization reaction with very large changes of viscosity as conversion proceeded) heat release data and heat transfer data simultaneously.

Possibly one can get the desired results from even simpler equipment. The objectives are:
- measure the instantaneous heat release or heat absorption rate of a sample;
- estimate heat transfer properties of the sample to the extent needed to adjust calibration;
- use the most simple and inexpensive equipment available to achieve this goal.

The following discussion assumes that a jacketed vessel is used and heat flow is controlled by adjustment of the jacket temperature. Two temperatures are measured by sensors placed into the jacket fluid and into the sample.

The real system is extremely difficult to describe mathematically. There are time-dependent local temperature gradients in the jacket, within wall, and at the interface of the sample. Additional problems are caused by secondary heat flows ('losses') and by mechanical heat dissipation in the sample, caused by stirring.

Table 4. *Development Status of Heat Flow Calorimetry*

Application Area	Extent of Use
thermal process safety	**high**; probably too high. There is a lot of activity guided by the obligation to assume responsibility, or simply by fear. Much of the data now elaborated in RC1-type equipment might be obtained on a much smaller, less costly scale.
scaleup /scale-down (general process development)	**low** Probably less than 20% of the process development laboratories use heat flow calorimeters, although there is a serious need for better insight into the process basics and for more and better data.
monitoring synthesis work (heat as a tracer)	**very low** Heat flow calorimetry is barely used in synthesis laboratories where reactions and process procedures are initiated and where the 'process view' provided by heat flow calorimetry would lead to better laboratory procedures and faster implementation.

Table 5. *Key Success Factors for the Development of Methods*

Feature	X-Rays	Atomic Force Microscopy	Liquid Chromatography	Heat Flow Calorimetry
Fascination (Glamour)	++	++	–	– –
Mainstream interest	++	++	–	–
Obvious usefulness	++	++	?	?
Affordability				
– cost of acquisition	+	?	+	?
– cost of operation	+	+	+	+

To focus on the most difficult problem, the dynamics of temperature in the vessel wall, we simplify by neglecting:
- secondary heat flows (loss through the lid of the vessel, *etc.*);
- local variations of the fluid temperatures of the jacket and of the sample (as far as heat balance is concerned, not the gradients in the heat transfer resistance);
- the dynamics of the temperature sensors.

The heat balance over the sample results in

$$\dot{T}_s \bullet (m \bullet c_p)_s = q_s - q_f \qquad (5)$$

with q_s = heat evolved in the sample (including heat dissipation by stirring),
q_f = heat flow from the sample to the jacket,
$(m \cdot c_p)_s$ = heat capacity of the sample.
- The simplistic approach is

$$\dot{T}_s = 0 \rightarrow q_s = q_f \text{ with } q_f = U \bullet A\,(T_s - T_j) \qquad (6)$$

- The next step of sophistication (to allow for time lag in the temperature adjustment of the jacket) is

$$q_s = q_f + \dot{T}_s \bullet (m \bullet c_p)_s \text{, assuming still } q_f = U \bullet A \bullet (T_s - T_j) \qquad (7)$$

To obtain a decent q_s-signal, T_j must be adjusted smoothly and fast.

When we want to allow considerable deviations of T_j from the value making $q_f = q_s$ and use temperature transients in the sample caused by such deviations to determine the heat transfer resistance (which is affected by the sample side film heat transfer coefficient, varying with time), we must take into account the dynamics of the temperature distribution in the wall. *Fig. 15* sketches the dynamics of the local temperature profiles. Heat flow out of the sample equals heat flow into the wall on the sample side ($q_f = q_{w,s}$) and is only dependent of instantaneous local temper-

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ature distribution (and not dependent of q_s). We can calculate the temperature distribution in the wall (including the sample-side wall surface temperature which determines q_f, the variable we are looking for) from the past history of the temperatures on both sides of the wall.

Karlsen, *Søberg*, and *Villadsen* [54] [55] did this with a BSC-81 in 1984 by heating and cooling the reactor contents from the jacket. The heat release calculated by the estimator (true value = 0) was within 0.2% of the heat transferred and the estimated heat release rates (true value = 0) were (as a 3-min mean) less than 4% of the mean heat transfer rates during the experiment (see [55], pp. 1170 and 1171). The results mentioned were obtained with a computer which was a hundred times 'weaker' than present laptop computers.

Thus, there is reason for hope that heat flow calorimeters can be built without very fast and highly accurate jacket temperature control. The only accessories needed to convert a conventional automated laboratory reactor into a calorimeter would be:

- a temperature sensor in the jacket,
- a high resolution of the reactor temperature,
- a calibration heater,

and, of course, algorithms for control, self-tuning, and evaluation.

The development effort will be high. And commercial success is achievable only if the resulting instrument

- is as easy or easier to use than a conventional laboratory reactor,
- has modest space requirements,
- has additional costs which are clearly outweighed by the value of additional information.

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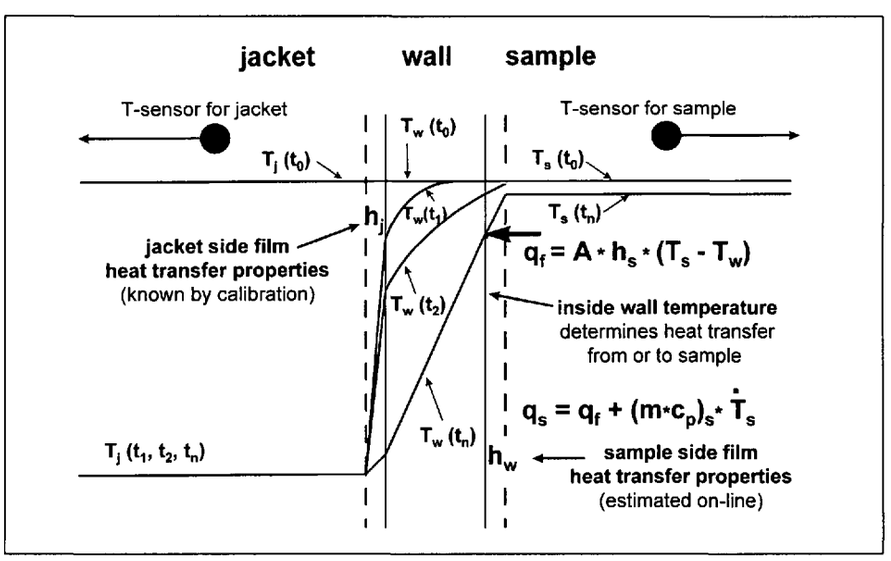

Fig. 15. *Change of local temperature profiles after a temperature change in the jacket fluid*