

## Extension of Heat Exchange Calorimetry to Continuously Stirred Tank Reactor and the Calorimetric Evaluation

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### Abstract

Heat exchange calorimetry is extended to continuously stirred tank reactor, CSTR, of flow type. Two glass vessels for sample and reference are fixed differentially in the precision water bath. Heat released in the sample vessel is exchanged freely with the ambient water. The temperature in each vessel is observed via a thermistor of small bead type constructed in Wheatstone bridge. The amplified output is introduced into analog computation circuit to calculate total heat effect. On the stopper of each vessel, solution inlet, heater element, thermistor and outlet for overflow are installed. In the present work, all examinations are carried out by water. As constancy of peristalsis pumps to send the solution was not so well for setting silicone tubing, the flow rate should be observed at every setting from time and mass measurements. Necessary evaluations for precision and reproducibility in the range from 3 to 73J are executed by electric heating and successful results were obtained for flow rate of 25, 16, 7 and 0 g/min which corresponded to batch type calorimeter.

### Introduction

Some continuously stirred tank reactors, CSTR, have been used to study non-linear chemical reactions<sup>1),2)</sup> by means of electrochemistry and spectroscopy. On the other hand, Lamprecht<sup>3)</sup> and Roelofs<sup>4)</sup> had reported calorimetric data of batch type concerning Belousov-Zhabotinskii reactions. However, chemical oscillation reactions by CSTR may continue for a long time in the steady state owing to continuous supply of necessary constituents. Therefore, CSTR for calorimetric measurements may be indispensable for the study of chemical oscillation reactions. Unfortunately, however, it may be difficult to design the CSTR in the common adiabatic calorimetry.

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The heat exchange calorimetry was developed by Nakanishi and Fuji-eda<sup>5)</sup> for the direct measurement of heat evolution in liquid—liquid or liquid—solid reactions, even if the reaction may be such speedily caloric phenomena as a step function. The fundamental concept is different from the usual adiabatic calorimetry. Sample and reference vessels are fixed differentially in a precision water bath. Heat released in the sample vessel was exchanged freely with the ambient water. The temperature change in the sample vessel was observed by a thermistor against that in the reference vessel, from which electric signals were obtained via Wheatstone bridge followed by the analog treatment for calculating total heat effect. The calorimeter is simply assembled and characterized by speedy attainment to thermal equilibrium and the easy handling of the measuring system. The calorimetry was also applied to the thermometric titrations<sup>6)</sup> as well as injection enthalpimetric analyses for precipitation reactions<sup>7)</sup>.

In thermometric and enthalpimetric titrations, a small amount of concentrated titrant had been added customarily to a large amount of dilute titrand or the solution to be titrated to prevent from increase in the volume and heat capacity. In practice, however, such several difficulties arose as (1) deposition of precipitate in the titration procedure, (2) large amount of heat of dilution concerned, (3) precise treatments of the small volume and (4) preparation of concentrated titrant by less soluble substances. In the previous work<sup>6)</sup>, a large amount of dilute titrant was added to the titrand, effect of volume increment being compensated by the analog computation circuit. Since the titrant was thermally equilibrated with the temperature of bath water prior to the addition and sent speedily, apparent heat effect was observed additionally in the reaction vessel which was also compensated in the analog circuit.

In the present work, titration calorimetry<sup>6)</sup> was modified in the theoretical background to the flow type of heat exchange calorimetry. The flow calorimeter was assembled by the authors for the purpose of CSTR, and the calorimetric precision and repeatability were examined by electric heating released from the heater element installed in the sample vessel.

### Theoretical Background

Sample and reference vessels are abbreviated as S and R, respectively, and each lowercase letter is used for physical amount. Temperature of the bath water was controlled precisely at  $T_a$ . Heat effect evolved in S, whose endothermic or exothermic evolution is expressed only by the sign, may be exchanged freely with the ambient bath water. In the calorimetry, it was assumed that there was no temperature gradient in the

water bath and both of vessels, and that heat evolved in S was homogenized instantaneously within the vessel.

When volume increase in S does not occur or is negligibly small, as measuring joule heat with the installed heater element and estimating heat of solution by adding a small amount of solid sample to liquid, the relation between heat evolving rate  $q$  and actual temperature  $T_s$  in S at time  $t$  can be expressed by the equation,

$$dT_s/dt = (q/W) - \alpha(T_s - T_a) \quad (1)$$

where  $\alpha$  is a constant related to heat transfer with the surroundings, and  $W$  is the effective heat capacity to avoid the confusion with capacitance  $C$  in the analog computation circuit. From the definition of  $R$ , eq. (2) was derived from eq. (1).

$$dT_r/dt = -\alpha(T_r - T_a) \quad (2)$$

The temperature in two vessels was treated differentially as follows:

$$T = T_s - T_r \quad (3)$$

Equation (4) was obtained in combination from eq. (1) to eq. (3).

$$dT/dt = (q/W) - \alpha T \quad (4)$$

On the other hand, in the titration calorimetry<sup>6)</sup>, in which the titrant solution was sent at a constant rate  $v$ , the volume to be titrated increased in S, so that  $W$  and  $\alpha$  in eq. (4) were also changed to  $W'$  and  $\alpha'$ . Additionally, titrant solution was equilibrated to  $T_a$  before sending to S. Heat evolving rate  $q'$  owing to temperature difference between  $T_s$  and  $T_a$  should be included in the course of titration. Therefore, eq. (4) may be changed to eq. (5).

$$dT/dt = (q + q')/W' - \alpha' T \quad (5)$$

The detailed expressions of  $q'$  and  $W'$  were as follows:

$$W' = W_0 + \rho cvt \quad (6)$$

$$q' = -\rho cv(T_s - T_a) = -\rho cvT \quad (7)$$

where suffix 0 in  $W_0$  means before the titration,  $\rho$  and  $c$  are density and heat capacity of the reaction solution, respectively. The constant  $\alpha'$  was directly proportional to heat exchange area in S and inversely proportional to the effective heat capacity. If heat in S was transferred only from the side wall of a cylindrical vessel, the heat exchange area may be proportional to liquid volume in S. The bottom of the cylindrical vessel S was covered effectively by experiment with thermal insulator board. Heat transfer in the surface to air was negligibly small. However, the  $\alpha'$

might be different from  $\alpha$  in the value.

As for the flow calorimetry, in the present work, the volume  $V$  in S and then  $W$  were not changed during the reaction. However, the heat evolving rate may be reversely proportional to  $V$  of the vessel used, and could be expressed as  $q''$  differing from  $q'$ . The reaction solution equilibrated to  $T_a$  was introduced to S at a constant flow rate  $v$ . The  $(T_s - T_a)$  was observed against  $(T_r - T_a)$  as indicated in eqs. (1) to (3). Therefore, eq. (4) was changed to eq. (8),

$$dT/dt = (q + q'')/W - \alpha T \quad (8)$$

where

$$q'' = -\rho cvT/V. \quad (9)$$

From eqs. (8) and (9), eq. (10) may be given for the heat exchange calorimetry of flow type in contrast to eq. (4).

$$dT/dt = (q/W) - (\alpha_0 + (\rho cv/WV))T \quad (10)$$

If the right terms in eq. (10) are rewritten as  $(q/W) - AT$ , plots of  $A$  against  $v$  may be of linear relation. The intercept of  $\alpha_0$  corresponds to  $\alpha$  in the calorimetry of batch type and the slope of  $(\rho c)/(WV)$  was a constant in the same flow run, but inversely proportional to  $V$  of the vessel used.

In the actual instrumentation of eq. (4) or eq. (10),  $T_s$  and  $T_r$  of eq. (3) were observed via two thermistors installed in each vessel. The characteristics of resistance to temperature in two thermistors were selected to be as similar as possible. The observed signals,  $\theta_s$  and  $\theta_r$  are corresponded to  $T_s$  and  $T_r$ , respectively. Relation between  $T$  and  $\theta$  was expressed by eq. (11),

$$d\theta/dt = \beta(T - \theta) \quad (11)$$

where  $\beta$  is a constant concerning delay of response for all the measuring system. If eq. (11) is combined with eq. (4) to eliminate  $T$ , and then rearranged, total heat effect  $Q$  is expressed by eq. (12).

$$Q = 1/W \int q dt = (1/\beta) d\theta/dt + (1 + \alpha/\beta)\theta + \alpha \int \theta dt \quad (12)$$

On the other hand, the relation of input voltage  $E_i$  and output voltage  $E_o$  in the operational amplifier circuit was expressed by eq. (13) from the fundamental knowledge of electronic circuits.

$$E_o = -R_2/R_1 \left\{ (R_1 C_1) dE_i/dt + (1 + R_1 C_1/R_2 C_2) E_i + (1/R_2 C_2) \int E_i dt \right\} \quad (13)$$

In the comparison of eq. (12) with eq. (13),  $\theta$  may be proportional to  $E_i$

and  $Q$  to  $E_o$ , provided that relations of  $\beta=(R_1C_1)^{-1}$  and  $\alpha=(R_2C_2)^{-1}$  were valid. Therefore, the  $Q$  may be estimated as  $E_o$  via eq. (13) or the analog circuit from  $E_i$  of observed electronic signals.

If the variable resistor  $R_2$  in the analog circuit or  $(R_2C_2)^{-1}$  is adjusted correctly to the  $\alpha$  which is changed with  $v$ , the appropriate  $Q$  to each  $v$  may be estimated by the analog computation circuit.

## Experimental

### *Reagents and apparatus*

Deionized water was used in all examinations.

An acryl box  $30 \times 30 \times 45 \text{ cm}^3$  in size was used as the water bath whose all surfaces were covered with thermally insulating boards of 2.8 cm thick. The bath water of  $36 \text{ dm}^3$  was held at  $25.0 \pm 0.1^\circ\text{C}$  by temperature controller (CTE 220, Taiyo Kogyo Co., Tokyo) and agitated continuously with a motor-driven stirrer (30W, LT-31, Yamato Kagaku Co., Tokyo). Sample and reference vessels made of glass which were placed on each magnetic stirrer of submarine type (M-3, Iuchi Seieido Co., Tokyo) were fixed in the water bath. In each vessel, solution inlet, electric heater element, thermistor as a temperature sensor and over flow outlet were fixed in the order. The geometric configuration was selected in connection to the rotation of stirrer. The inside of two vessels was made as the same as possible and also minimized as possible for effective heat capacity.

The reaction solution was introduced to S by peristalsis pump (MP-3, Eyela Microtube Pump, Tokyo Rika Kikai Co., Tokyo) via silicone tubing of 1.5 mm, 3 mm and 5 mm inside diameter and 5 m length held in the water bath to prevent from the pulse flow and to equilibrate thermally the solution. The reference solution was similarly introduced to R. In the work, water was used for both solutions. The precise flow rates from 1.5 to 30 g/min were obtained by measuring time and mass.

The heater element installed in each vessel for measuring joule heat was made of resistor (1/8W, 985 $\Omega$ ) coated with epoxy resin paste. Thermistors in S and R were of bead type (MB, Tekunoseven Co., Tokyo).

Electric signal  $E_i$  was obtained as output of Wheatstone bridge followed by preamplifier (PM-16A, Toa Dempa, Co., Tokyo), and then introduced as input signal to the analog computation circuit. The  $E_o$  was monitored with  $Y-t$  recorder (R-02, Rika Denki Co., Tokyo).

### *Procedure*

Sample and reference vessels were fixed in the water bath filled with necessary amount of water. After setting the temperature of bath water

on the operation panel, the temperature controller was started. Water was sent continuously to each vessel from peristalsis pumps during a series of experiments, each flow rate being measured. Thermal equilibrium of the flow system in water bath and warming up of electric circuits might be attained after 40 min or more. Then, from the trail of  $E_0$  vs.  $t$  on the recorder chart observed by electric heating, time constant of  $R_2C_2$  in the analog computation circuit was adjusted to coincide with the constant  $\alpha$  of the calorimeter by turning variable resistor of  $R_2$ . The adjusted analog circuit was used for the caloric evaluation of the heat exchange calorimeter in flow type.

### Results and Discussion

The constant  $B$  and resistance  $R$  of a thermistor were defined as  $R = A \exp(BT^{-1})$ . The  $B$  and  $R$  of each thermistor  $Th_S$  and  $Th_R$  installed in two vessels were estimated experimentally. The  $R$ 's of 8 points were observed in cooling direction between 35.0°C and 12.8°C, and those of 15 points in heating direction between 14.0°C and 36.0°C. The clear difference between the measured values in two directions was not shown at each linear plot of  $\ln R$  vs.  $T^{-1}$  for  $Th_S$  and  $Th_R$ . The regression expressions of least squares for  $Th_S$  and  $Th_R$  were given as  $\ln R = 3455.0T^{-1} - 2.977$  with correlation coefficient of 0.997 and  $\ln R = 3455.3T^{-1} - 2.982$  with correlation coefficient of 0.998, respectively. In the calculations, too much significant figures were written, but it was necessary to indicate the difference in two  $B$  constants. The  $B$  constants of  $Th_S$  and  $Th_R$  were estimated to be 3455.0K and 3455.3K, respectively, and their resistance 5.605k $\Omega$  and 5.586k $\Omega$ , respectively, at 25.0°C.

A peristalsis pump is commonly used to sending liquid including chemicals in moderate speed. In the present work, the pump was also selected from economic conditions in spite of the poor repeatability and constancy. The results observed for the most popular range were shown in Table 1. It was concluded for setting of silicone tubing to the peristalsis pump that the constancy in each run was passable, but the repeatability for separate runs was not satisfied. Then, the duration of constancy was also examined for enough long time. The detailed plots of  $v_s$  vs.  $t$  were shown as Fig. 1, in which A, B and C were measured at dial 7, 5 and 3, respectively, of the pump used. In practical experiments,  $v_s$  and  $v_r$  should be monitored as indicated from the observed results.

As usual in the calorimetry, in the present work, the heat evolution by the heater element installed in the vessel was preferred to any chemical reactions to test the performance of the assembled calorimeter, because the

Table 1. Reproducibility test in setting the silicone tubing to the peristalsis pump.

setting No.	1			2			3		
$w / g$	16.66	20.91	27.38	4.89	9.73	14.54	4.48	8.92	13.34
$t / \text{min}$	4.0	5.0	6.5	1.0	2.0	3.0	1.0	2.0	3.0
$v / \text{gmin}^{-1}$	4.17	4.18	4.21	4.89	4.87	4.85	4.48	4.46	4.45

Table 2. Heat correction value for  $v_s=0$  g/min.

$v_s$ (g/min)	$E$ (V)	$t$ (s)	$Q$ (J)	$H$ (cm)	observed $h$ (J/cm)	mean (J/cm)	$h$ (J/cm)	
0	15.41	15.00	3.62	12.95	0.2795 <sup>a</sup>	0.2776	5.563	
0	15.41	15.00	3.62	12.97	0.2791 <sup>a</sup>	$\pm 0.0030$	5.563	
0	15.41	15.32	3.69	13.46	0.2741 <sup>a</sup>	( $\pm 1.08\%$ )	5.512	
0	15.41	13.34	3.22	5.85	0.5497 <sup>b</sup>		5.497	
0	15.41	13.76	3.32	5.95	0.5575 <sup>b</sup>	0.5540	5.575	
0	15.41	13.84	3.34	6.02	0.5542 <sup>b</sup>	$\pm 0.0029$	5.542	
0	15.40	44.84	10.80	19.55	0.5522 <sup>b</sup>	( $\pm 0.54\%$ )	5.522	
0	15.40	43.24	10.41	18.75	0.5538 <sup>b</sup>		5.538	
0	15.40	43.59	10.50	18.85	0.5568 <sup>b</sup>		5.568	
0	15.41	130.01	31.37	11.30	2.776 <sup>c</sup>		5.529	
0	15.41	129.61	31.25	11.24	2.780 <sup>c</sup>		5.538	
0	15.41	129.40	31.20	11.21	2.783 <sup>c</sup>		5.544	
0	15.41	129.38	31.19	11.20	2.785 <sup>c</sup>		5.548	
0	15.42	171.36	41.58	14.88	2.780 <sup>c</sup>	2.766	5.538	
0	15.42	171.58	41.58	14.92	2.776 <sup>c</sup>	$\pm 0.019$	5.530	
0	15.42	171.58	41.58	14.91	2.778 <sup>c</sup>	( $\pm 0.69\%$ )	5.534	
0	15.42	217.45	52.49	19.10	2.748 <sup>c</sup>		5.475	
0	15.42	258.21	62.33	22.78	2.736 <sup>c</sup>		5.451	
0	15.42	262.07	62.35	23.03	2.747 <sup>c</sup>		5.472	
0	15.43	258.12	62.39	22.79	2.738 <sup>c</sup>		5.453	
0	15.43	300.09	72.54	13.32	5.446 <sup>d</sup>	5.449	5.446	
0	15.43	300.10	72.54	13.32	5.446 <sup>d</sup>	$\pm 0.005$	5.446	
0	15.43	300.30	72.59	13.31	5.454 <sup>d</sup>	( $\pm 0.09\%$ )	5.454	
							5.514 $\pm$ 0.043	
								( $\pm 0.78\%$ )

Recorder range in full scale: a, 0.5 V; b, 1 V; c, 5 V; d, 10 V

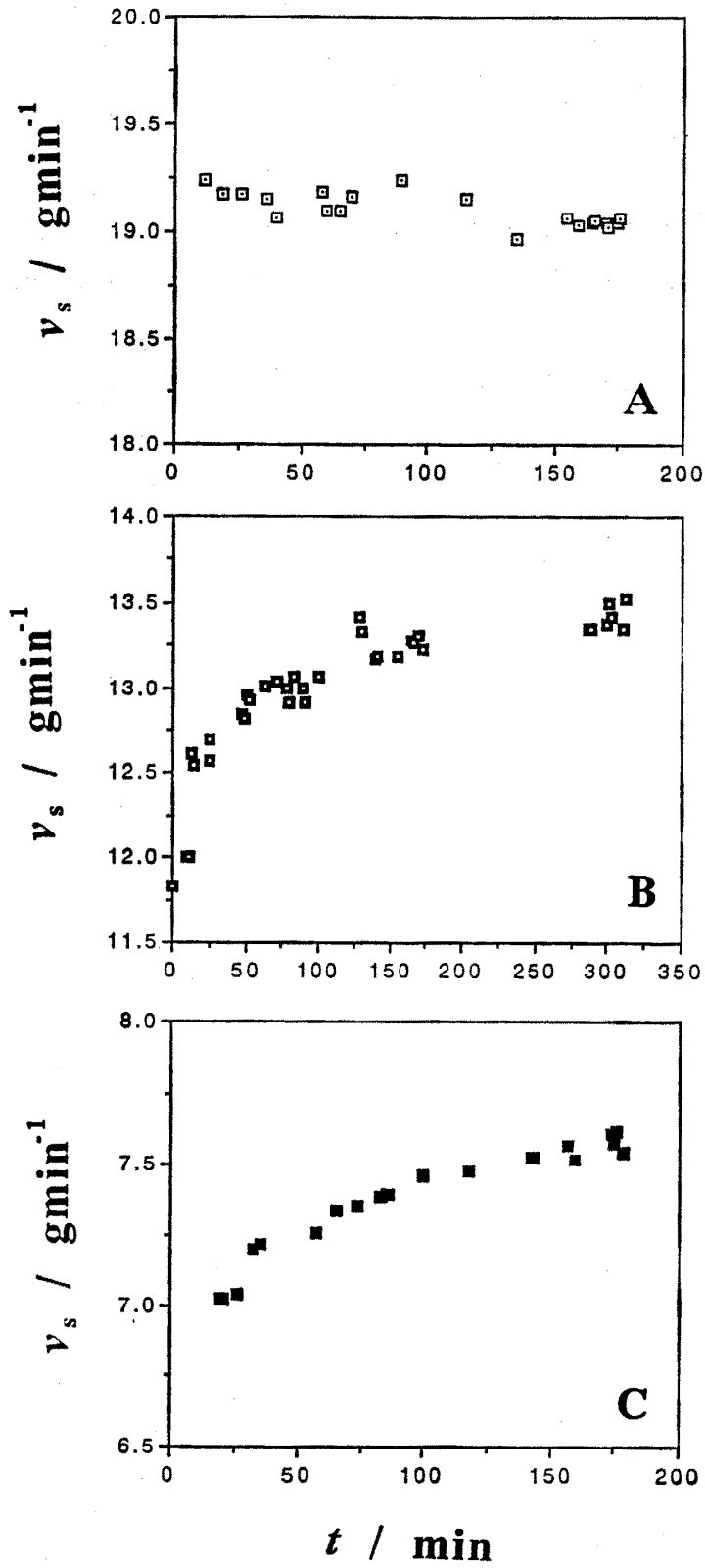


Fig. 1. Constancy test for the peristalsis pump used:  
A, at dial 7; B, at dial 5; C, at dial 3.



Table 3. Heat correction value for  $v_s=7$  g/min.

$v_s$ (g/min)	$E$ (V)	$t$ (s)	$Q$ (J)	$H$ (cm)	observed $h$ (J/cm)	mean (J/cm)	$h$ (J/cm)
6.54	15.41	14.07	3.39	10.80	0.3139 <sup>a</sup>	0.3195	6.278
6.56	15.41	15.02	3.62	11.12	0.3255 <sup>a</sup>	$\pm 0.0058$	6.510
6.56	15.41	13.26	3.20	10.03	0.3190 <sup>a</sup>	( $\pm 1.82\%$ )	6.380
6.59	15.41	44.00	10.61	16.55	0.6411 <sup>b</sup>	0.6465	6.411
6.58	15.41	43.92	10.59	16.32	0.6489 <sup>b</sup>	$\pm 0.0047$	6.489
6.59	15.41	42.97	10.36	15.95	0.6495 <sup>b</sup>	( $\pm 0.73\%$ )	6.495
6.59	15.41	132.08	31.84	9.90	3.216 <sup>c</sup>		6.407
6.60	15.41	128.13	30.89	9.68	3.191 <sup>c</sup>		6.357
6.59	15.41	127.96	30.85	9.65	3.197 <sup>c</sup>		6.368
6.58	15.41	172.85	41.28	13.10	3.181 <sup>c</sup>		6.337
6.64	15.42	171.05	41.29	13.05	3.193 <sup>c</sup>	3.212	6.361
6.68	15.42	170.76	41.22	12.92	3.190 <sup>c</sup>	$\pm 0.025$	6.355
6.63	15.42	217.10	52.41	16.37	3.202 <sup>c</sup>	( $\pm 0.78\%$ )	6.378
6.68	15.42	216.28	52.21	16.10	3.243 <sup>c</sup>		6.460
6.64	15.42	216.18	52.19	16.20	3.222 <sup>c</sup>		6.418
6.65	15.41	258.14	62.23	19.40	3.208 <sup>c</sup>		6.390
6.69	15.41	255.67	61.64	19.02	3.241 <sup>c</sup>		6.456
6.69	15.42	268.01	64.70	19.85	3.259 <sup>c</sup>		6.493
6.69	15.41	304.20	73.34	11.50	6.377 <sup>d</sup>	6.356	6.377
6.69	15.42	300.27	72.48	11.40	6.358 <sup>d</sup>	$\pm 0.022$	6.358
6.67	15.42	304.34	73.47	11.60	6.334 <sup>d</sup>	( $\pm 0.35\%$ )	6.334
6.63 $\pm 0.05$ ( $\pm 0.75\%$ )							6.401 $\pm$ 0.062 ( $\pm 0.97\%$ )

Recorder range in full scale : a, 0.5 V ; b, 1 V ; c, 5 V ; d, 10 V

desired heat with perfect repeatability was produced easily at any time. The observed results are summarized from Table 2 to 5. Water was sent to two vessels, S and R, from each peristalsis pump at the same speed as possible. Both  $v_s$  and  $v_r$  were measured, but only  $v_s$  was shown in the tables. The  $v_s$  values shown as mean and its standard deviation in the bottom line in each table except Table 2 were considered to indicate the reproducibility for one setting. The runs in Table 2 corresponded to the calorimetry by batch type. By applying voltage  $E$  to the heater element for time  $t$  the total heat effect  $Q$  was released. The input full scale of 3 mV was usually used as preamplifier range. The  $H$ 's in the tables were obtained as output voltage of the analog circuit followed by the  $Y-t$  recorder. The calorimetric estimations observed by the assembled calorimeter of flow type were satisfied as shown in the bottom line of heat cor-

Table 4. Heat correction value for  $v_s=16$  g/min.

$v_s$ (g/min)	$E$ (V)	$t$ (s)	$Q$ (J)	$H$ (cm)	observed $h$ (J/cm)	mean (J/cm)	$h$ (J/cm)
16.04	15.38	14.11	3.39	9.75	0.3477 <sup>a</sup>	0.3558	6.954
16.04	15.37	15.40	3.69	10.39	0.3551 <sup>a</sup>	$\pm 0.0063$	7.103
16.06	15.37	15.31	3.67	10.11	0.3630 <sup>a</sup>	( $\pm 1.77\%$ )	7.260
16.06	15.37	15.41	3.70	10.35	0.3575 <sup>a</sup>		7.150
16.10	15.37	45.59	10.93	15.40	0.7097 <sup>b</sup>	0.7040	7.097
16.02	15.38	43.07	10.34	14.76	0.7005 <sup>b</sup>	$\pm 0.0050$	7.005
16.02	15.37	45.53	10.92	15.56	0.7018 <sup>b</sup>	( $\pm 0.71\%$ )	7.018
16.00	15.38	128.98	30.97	8.81	3.515 <sup>c</sup>		7.003
15.98	15.38	130.80	31.41	8.95	3.509 <sup>c</sup>		6.991
16.05	15.38	124.28	29.85	8.72	3.423 <sup>c</sup>		6.819
16.00	15.38	174.90	42.00	11.96	3.512 <sup>c</sup>		6.995
15.98	15.38	169.98	40.82	11.72	3.483 <sup>c</sup>	3.507	6.938
15.99	15.38	156.28	37.53	10.80	3.475 <sup>c</sup>	$\pm 0.033$	6.922
15.99	15.38	215.10	51.66	14.60	3.538 <sup>c</sup>	( $\pm 0.94\%$ )	7.049
16.03	15.38	215.43	51.73	14.77	3.502 <sup>c</sup>		6.977
15.85	15.38	214.84	51.59	14.58	3.538 <sup>c</sup>		7.049
15.64	15.38	259.06	62.21	17.63	3.529 <sup>c</sup>		7.029
15.72	15.38	256.75	61.66	17.43	3.538 <sup>c</sup>		7.047
15.76	15.38	259.66	62.36	17.72	3.519 <sup>c</sup>		7.010
15.83	15.38	300.11	72.07	10.12	7.122 <sup>d</sup>	7.123	7.122
15.85	15.39	300.33	72.22	10.15	7.115 <sup>d</sup>	$\pm 0.009$	7.115
15.90	15.39	293.05	70.47	9.88	7.133 <sup>d</sup>	( $\pm 0.13\%$ )	7.133
15.95 $\pm 0.12$ ( $\pm 0.75\%$ )							7.036 $\pm$ 0.093 ( $\pm 1.32\%$ )

Recorder range in full scale : a, 0.5 V ; b, 1 V ; c, 5 V ; d, 10 V

rection  $h$ . The regression expression of least squares was calculated to be  $h = 0.1157 v_s + 5.499$  with correlation coefficient of 0.972. In practical experiments, however, it may also be recommended to measure  $h$  for each run owing to keeping the higher calorimetric precision.

Table 5. Heat correction value for  $v_s=25$  g/min.

$v_s$ (g/min)	$E$ (V)	$t$ (s)	$Q$ (J)	$H$ (cm)	observed $h$ (J/cm)	mean (J/cm)	$h$ (J/cm)
24.97	15.40	14.04	3.38	8.37	0.4038 <sup>a</sup>	0.4135	8.076
24.97	15.40	14.00	3.37	8.05	0.4186 <sup>a</sup>	$\pm 0.0077$	8.373
25.01	15.40	14.01	3.37	8.20	0.4110 <sup>a</sup>	( $\pm 1.86\%$ )	8.220
25.12	15.40	13.55	3.26	7.75	0.4206 <sup>a</sup>		8.413
25.22	15.40	44.78	10.78	12.96	0.8318 <sup>b</sup>	0.8467	8.318
25.24	15.40	44.53	10.72	12.49	0.8583 <sup>b</sup>	$\pm 0.0135$	8.583
25.21	15.40	44.05	10.61	12.65	0.8387 <sup>b</sup>	( $\pm 1.59\%$ )	8.387
25.30	15.41	45.53	10.98	12.80	0.8578 <sup>b</sup>		8.578
25.05	15.41	127.58	31.41	7.10	4.332 <sup>c</sup>		8.629
25.20	15.41	130.19	31.39	7.25	4.330 <sup>c</sup>		8.625
25.21	15.41	130.21	31.39	7.32	4.288 <sup>c</sup>		8.542
25.22	15.41	172.92	41.69	9.45	4.412 <sup>c</sup>		8.788
25.30	15.42	172.28	41.59	9.45	4.401 <sup>c</sup>	4.361	8.767
25.35	15.42	174.55	42.14	9.68	4.353 <sup>c</sup>	$\pm 0.043$	8.672
25.40	15.42	216.69	52.31	11.88	4.403 <sup>c</sup>	( $\pm 0.99\%$ )	8.771
25.38	15.42	217.31	52.46	12.15	4.318 <sup>c</sup>		8.601
25.30	15.42	219.14	52.67	12.22	4.329 <sup>c</sup>		8.624
25.49	15.42	258.17	62.32	14.27	4.367 <sup>c</sup>		8.700
25.56	15.42	258.35	62.37	14.25	4.377 <sup>c</sup>		8.719
25.51	15.42	258.15	62.32	14.08	4.426 <sup>c</sup>		8.817
25.58	15.42	299.96	72.41	8.30	8.724 <sup>d</sup>	8.748	8.724
25.60	15.42	300.27	72.48	8.28	8.754 <sup>d</sup>	$\pm 0.021$	8.754
25.55	15.42	300.29	72.49	8.27	8.765 <sup>d</sup>	( $\pm 0.24\%$ )	8.765
25.29 $\pm 0.19$ ( $\pm 0.75\%$ )							8.585 $\pm 0.198$ ( $\pm 2.31\%$ )

Recorder range in full scale : a, 0.5 V ; b, 1 V ; c, 5 V ; d, 10 V

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