Soil Removal in Relation to Total Work Input; A Calorimetric Approach for Model Wash Systems

L. LOEB and R. O. SHUCK, Major Appliance Laboratories, General Electric Co., Louisville, Kentucky 40225

Abstract

A simple, straightforward method, utilizing the concepts of classical adiabatic calorimetry, for direct measurement of total energy delivery to bench scale clothes washing systems is described. The results of such measurements can be expressed in conventional work units such as calories per unit weight or per unit area of fabric. Using this method, total energy input is measured and related to soil removal in model wash systems using a standard cotton soil cloth. The relationship between energy input and soil removal is considered for a number of situations involving variations in stroke rate, load weight and detergent concentration. Finally, these results are used to develop a modified definition of detergency which places the emphasis on the efficiency of mechanical energy utilization in a soil removal process.

Introduction

In 1963 Bourne and Jennings (1) reviewed the existing definitions for the words "detergent" and "detergency." They then proposed the following definition: "A detergent is any substance that, either alone or in a mixture, reduces the work requirement of a cleaning process." Viswanadham and Rao (2) have commented on this definition and criticized it on at least three counts: it is too broad; it delegates detergent action to substances which do not strictly possess such power; and it overemphasizes the mechanistic aspects of the processes at the expense of physicochemical action.

While this discussion on definitions is of interest in its own right, it appears that both of these short communications are admirable in another sense: they again call attention to the importance of energy considerations in the characterization of detergent action and detergency processes. When one attempts to apply the definition cited above to the characterization of real detergency processes, it becomes immediately apparent that there is almost no information on the relationships of energy input and soil removal either in the absence or presence of detergent-like materials. Twenty years ago Bacon and Smith (3) stressed the importance of mechanical action in detergency and discussed the importance of detergents in reducing the work requirements for cleaning. They examined the effect of varying force factors on soil removal. However, they employed an arbitrary force scale not directly reducible to conventional energy units. More recently, Tuzson and Short (4) have discussed power consumption in the Terg-O-Tometer during fabric washing but did not give any information on soil removal in relation to power consumption.

The purpose of this communication is to describe a simple, straightforward method which we have used for several years to measure the total energy delivery to bench scale clothes washing systems, and to relate total energy input and soil removal for model systems using a standard cotton soil cloth. The results of the method to be described allows the energy input to be expressed in conventional work units such as calories per gram or calories per unit area of fabric being cleaned. With such data available it should be possible to specify quantitatively the reduction in work requirements effected by the detergent as called for in the Bourne definition.

Experimental Procedure

A calorimetric technique has been devised for measuring the total energy input to bench scale model wash systems. In theory, the requirements of this approach are quite simple. We first assume a thermally isolated wash system containing a known volume of detergent solution and a known weight of soiled fabric. If, then, a given amount of mechanical energy is delivered into this isolated system, the heat content must be increased by an amount dependent only on the mechanical energy delivered. The measurement of such changes in heat content of the system requires only that a method be available for accurately following temperature changes during the mechanical agitation period, that the heat equivalent of the total system be known, that there be no appreciable exchange of heat between the bath and its surroundings, and that any heat effects associated with the interaction of the fabric substrate and the detergent bath be dissipated during an equilibration period prior to the agitation period.

A schematic drawing of the apparatus devised for these measurements is shown in Figure 1. In order to isolate the wash system thermally, a silvered vacuum flask of 4⅝ in. i.d. was used to contain the bath. The flask was closed with a ½ in. close fitting plastic lid. To reduce further the possibility of heat transfer with the surroundings, the wash runs were made at room temperature (76 ± 1 F.) using a cold water liquid laundry detergent, containing approximately 10% nonionic surfactant and a potassium pyrophos-

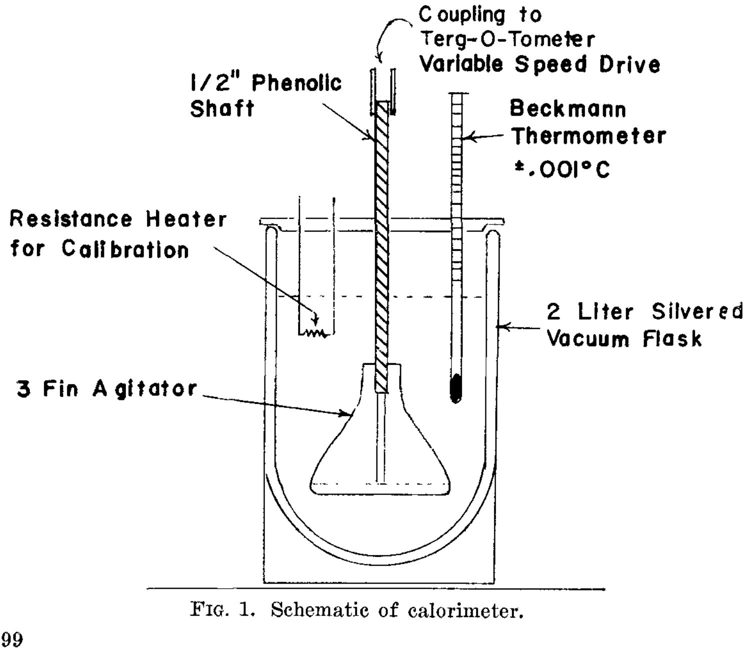

FIG. 1. Schematic of calorimeter.

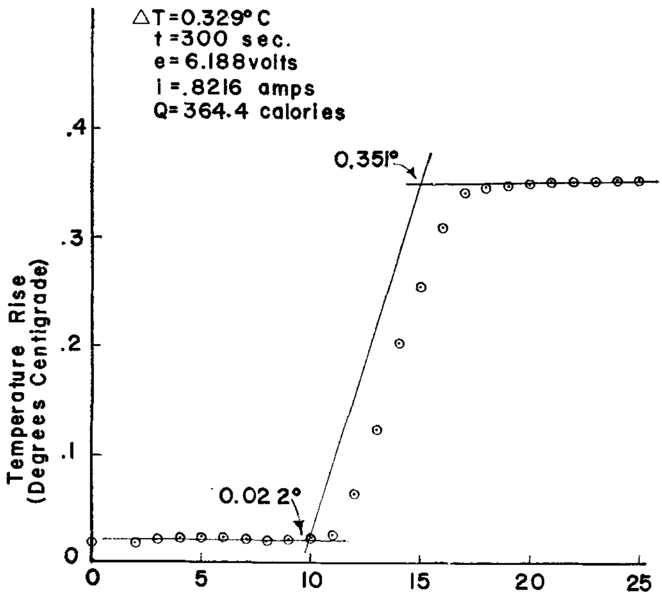

FIG. 2. Heat equivalent determination.

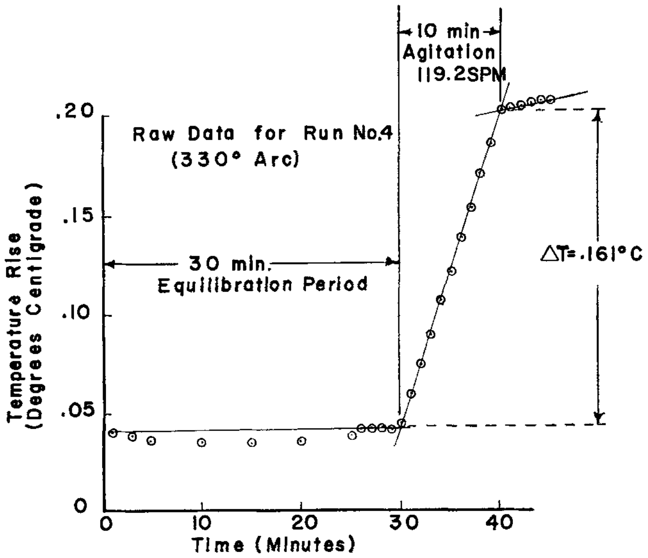

FIG. 3. Typical time-temperature curve for calorimeter.

phate builder. Further details of the experimental set-up were: Fabric loads, 20 to 40 g measured to ±.001 g air dry weight. Soil fabric, USTC standard cotton soil cloth. Clean fabric, USTC unsoiled cotton (same fabric as used for preparation of soil cloth). Water, 1000 ml distilled. Thermometer, Beckmann readable to ±0.001 C. Agitator, 3 fin Terg-O-Tometer agitator mounted on ½ in. phenolic shaft.

The small resistance heater shown in Figure 1 was used to determine the heat equivalent of the calorimeter and was withdrawn from the bath during subsequent soil removal runs. For the determination of the heat equivalent, the flask was filled with 1000 ml of detergent solution containing 0.2% detergent solids, 30 g of clean cotton fabric in the form of 3 × 4 in. swatches, and the shaft and agitator were placed in position for normal agitation. The small heater was lowered into the bath. The solution was agitated at the lowest possible stroke rate (38 SPM) throughout the heat equivalent determination. After the system had reached thermal equilibrium, the heater was activated for 300 sec from a 6 v DC power supply. The temperature was measured at 1 min intervals throughout the run. The energy output of the heater was calculated as follows: $Q = Jeit$, where: Q = heat delivered to bath in gram calories; J = conversion constant = 0.2389; e = potential across heater in volts; i = current flow in amperes; and t = time in seconds.

In a typical heat equivalent determination as shown in Figure 2 the temperature rise was 0.329 C in 300 sec. The calculated heat input was 364.4 calories and the calculated heat equivalent was 1108 calories per °C. The average for four replicate determinations was 1118 calories per °C.

To complete the description of this technique a typical soil removal run will be described. For the illustrative run the fabric load weighing 20.001 g and consisting of ten 3 × 4 in. USTC soil cloth swatches together with sufficient clean fabric swatches to complete the load was added to a 1000 ml wash bath containing 0.158% detergent solids. The bath was allowed to equilibrate for 30 min with very brief agitation, 1 sec/min, to prevent temperature stratification. The bath was then agitated continuously for 10 min at 119.2 strokes per minute with the arc length fixed at 330°. The temperature was read at 1 min intervals throughout the agitation period. The load was then rinsed for 5 min at the same stroke rate in a distilled water bath and allowed to line dry overnight prior to determining the final reflectance for the soil cloth swatches. The time-temperature plot for this run is shown in Figure 3. The measured temperature rise during the 10 min agitation period was 0.161 C. The product of the temperature rise and the heat equivalent gives the total energy input in calories; this was 179.9 calories for the run shown in Figure 3. For various purposes, it is usually more convenient to express the total work input per unit weight or area of fabric being washed. The USTC fabric has an air dry weight of 0.105 g/in^2 giving a one side area of 190.5 in^2 for the 20 g load. The total work input in calories per square inch was thus 0.944 calories per square inch of fabric.

Soil removal calculations were made in the usual manner via the Kubelka-Munk equation with reflectance determined both before and after washing using the Gardner CIE Automatic Colorimeter. The colorimeter was equipped with Corning No. 3389 Noviol filters to eliminate any ultraviolet radiation from the light source. The average calculated soil removal for the 10 swatches included in the illustration run was 59.3 ± 1.92%.

Results

While the calorimetric technique can and has been applied to the evaluation of several of the important mechanical variables of the washing process, the results cited will be limited mainly to those having a bearing on the detergent definition previously discussed.

In the first experimental series to be examined the detergent concentration was fixed at 0.158% solids (6 g/gal) for all runs. Likewise the soil cloth was fixed by taking all swatches from a single bolt of USTC standard cotton soil cloth (Lot No. 486). The plan was to wash 20, 30 and 40 g loads in 1000 ml baths at approximately 55, 80, 100 and 120 strokes per minute. The arc length of the stroke was not varied, but was fixed at 330°. The soil removal and

TABLE I

USTC Soil Cloth (Lot No. 486), 20, 30 and 40 g Loads

Run No.	Load weight, g	Stroke rate, SPM	Soil removal % $\pm\sigma_{10}$	Temp. rise °C	Increase in heat content (calories)
1	20	54.3	25.4 ± 3.6	0.022	24.6
2	20	79.7	37.2 ± 3.5	.054	60.4
3	20	98.8	52.4 ± 2.9	.093	103.9
4	20	119.2	59.3 ± 1.9	.161	179.9
5	30	54.8	20.0 ± 8.3	0.018	20.1
6	30	79.9	40.2 ± 6.4	.056	62.6
7	30	97.9	46.8 ± 6.4	.096	107.3
8	30	118.5	54.0 ± 2.0	.177	197.8
9	40	54.3	19.0 ± 9.4	0.019	21.2
10	40	79.4	36.9 ± 12.3	.059	65.9
11	40	100.0	44.8 ± 4.7	.111	124.1
12	40	118.2	52.3 ± 3.5	.117	197.8

temperature rise data for these 10 min washes are summarized in Table I.

Plots of soil removal vs. heat content increase are shown in Figure 4. From these curves one may read off the total energy input required at various levels of soil removal for each load size. These calculations for 30%, 40% and 50% soil removal are summarized in Table II.

The results show that at constant detergent concentration soil removal shows a consistent increase with increased energy input. However, when the work inputs are expressed on a per gram or per square inch basis, the energy requirements are roughly independent of load size.

Most of our experiments have been concerned with the effect of variations of mechanical parameters on energy delivery. However, one study was made wherein detergent concentration was the prime variable. In this experiment the detergent concentration was varied from 0% to 0.32% solids while the work input was maintained constant. From these results we can evaluate the efficiency of utilization of energy in the presence of increasing detergent concentration. Both 20 and 40 g loads were employed. For those runs the agitation stroke rate was fixed at 100 SPM and all runs were of 10 min duration. The data for the runs made with detergent concentration as the variable are summarized in Table III.

Plots of both soil removal and the increase in heat content are shown as a function of detergent concentration in Figure 5. As should be expected, the measured heat content increase is very nearly the same for all of these runs made on loads of fixed size. Also as expected, the soil removal increases strongly as detergent concentration was increased from 0% to about 0.15% solids; above 0.15% solids the soil removal is nearly constant.

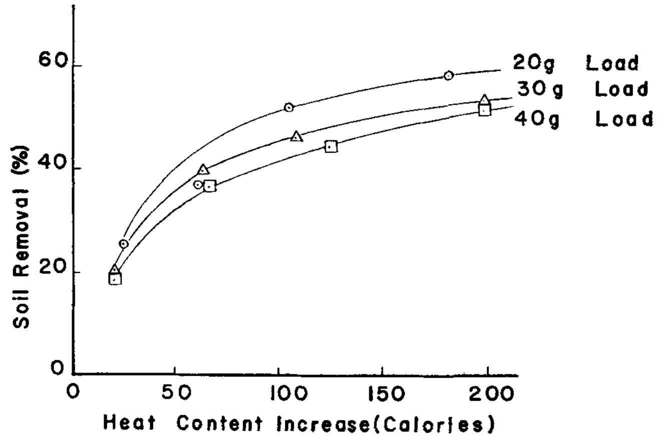

FIG. 4. Soil removal as a function of total energy input.

TABLE II

Energy Requirements for Soil Removal at Fixed Detergent Concentration

Load size, g	Soil removal, %	Heat content increase, (calories)	Calories per unit weight (cal/g)	Calories per unit area (cal/in²)
20	30	29	1.45	0.152
20	40	46	2.30	.242
20	50	86	4.30	.451
30	30	33	1.10	0.115
30	40	62	2.06	.216
30	50	139	4.63	.486
40	30	41	1.03	0.108
40	40	82	2.05	.215
40	50	175	4.37	.460

Discussion

In order to utilize the Bourne and Jennings definition in a fully quantitative sense it would be necessary to wash a series of loads to the same soil removal level in the presence of varying amounts of detergent. If one could know the total energy utilized to achieve equal soil removal at various detergent levels, the effects of the detergent in reducing the work requirement could be directly specified. However, the achievement of precisely equal soil removal for a range of detergent concentrations would be difficult to obtain experimentally and has not been attempted in our study. A slight modification of the Bourne definition makes it more directly usable in relation to our experimental data. We would define a detergent as follows: "A detergent is any substance that, either alone or in a mixture, increases the efficiency with which mechanical energy is utilized in a cleaning process."

This modified definition puts the emphasis on the efficiency of mechanical energy utilization. This efficiency ratio can be taken as the quotient of soil removal to work input and should be applicable to any level of soil removal provided that the work input

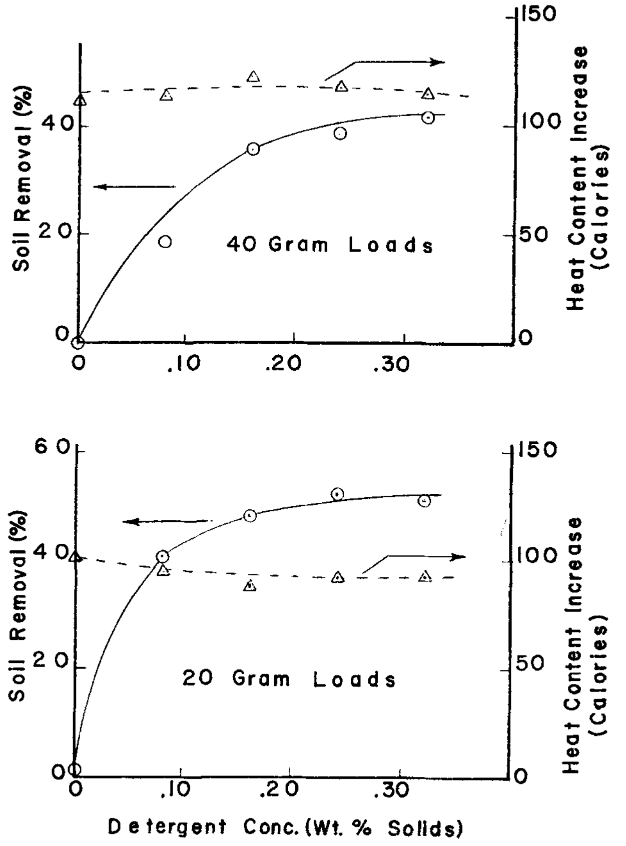

FIG. 5. Soil removal in relation to detergent concentration.

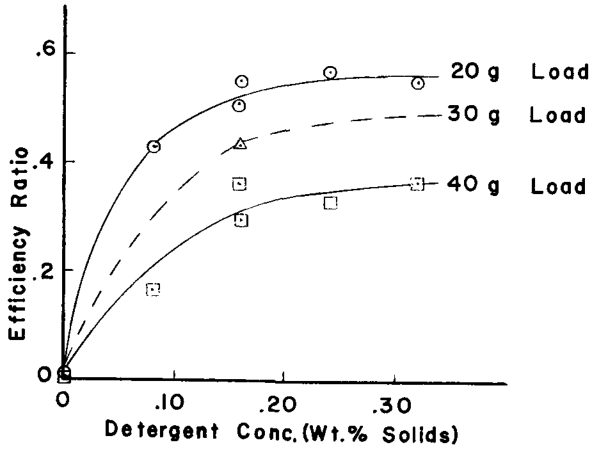

FIG. 6. *Soil removal efficiency in relation to detergent concentration.*

is known. This efficiency ratio, as defined above, has been calculated for a number of runs at 100 SPM agitation taken from the data of Tables I and III. The results of such calculations are shown graphically in Figure 6 where the efficiency ratios are plotted versus detergent concentration. It is apparent from this plot that, at least for the soil cloth used in these experiments, the utilization of mechanical energy is very poor in the absence of detergent and increases strongly with detergent concentration. As with soil removal, the efficiency ratio is essentially constant at detergent concentrations above 0.15% solids. The efficiency of utilization of mechanical energy in effecting soil removal is, however, strongly dependent on load size and therefore, on the bath-to-fabric ratio. While not proven, one would expect the ratio also to be dependent on the type of detergent employed and on the soil system employed as an indicator.

TABLE III

Soil Removal and Heat Data for USTC Soil Cloth at Various Detergent Concentrations

Run No.	Load weight, g	Detergent concentration (wt. % of solids)	Soil removal ($\% \pm \sigma_{10}$)	Temperature rise, °C	Heat content increase (calories)
1	20	.00	1.41 ± 1	0.091	101.7
2	20	.08	40.65 ± 5.11	.085	95.0
3	20	.16	48.16 ± 4.12	.078	87.1
4	20	.24	52.29 ± 3.05	.082	91.6
5	20	.32	51.14 ± 2.12	.083	92.8
6	40	.00	0.00	0.100	111.7
7	40	.08	18.62 ± 9.78	.102	114.0
8	40	.16	35.81 ± 7.60	.109	122.0
9	40	.24	38.65 ± 8.24	.106	118.5
10	40	.32	41.88 ± 5.76	.103	115.1

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