Characterization of Combustibles for Engineering Fire Calculations

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Abstract

In the engineering fire safety design, design fire scenario and/or design fire source would be assumed. Then the potential fire behavior is calculated by using engineering prediction methods. To assure the validity of design, the assumption of design fire scenario and fire source must be justified. At present, the assumption vastly relies upon expert judgments. However, rational basis shall be established. Fire load survey is probably the unique way to establish design fire scenario. Field survey yields fire load density (wood equivalent) and arrangement of combustible fuels.

By adopting the normal procedure for survey, size, location, weight and type of materials are recorded on site of survey. Consequently, field survey of combustible is usually time and cost consuming. As a result, existing knowledge is not enough to cover all the occupancies of interest. To increase the stock of survey data, practical methods of field survey shall be established.

In this study, survey was made on common combustibles to establish the correlations between characteristic size, weight, surface area, effective heat of combustion, and effective heat release rate per unit area. The results are summarized into categories (dairy goods, clothes, stationeries, kitchen goods and so on). By using the results, it is possible to make quick estimate of the fuel characteristics if surveyors know type and size (volume) of combustibles.

KEYWORDS: Combustibles, Survey, Characterization, Total Heat Release, Heat Release Rate

1. INTRODUCTION

In the process of performance-based fire safety design, it is necessary to establish a rational prediction of fire behavior that may take place in the design object in question. Field survey of combustible contents is often applied to obtain information on the type, amount and representative distribution of combustibles. In the past, many surveys were carried out. For ordinary occupancies where flashover fire is inevitable, total mass and/or heat of combustion is examined. The results are summarized in the form of fire load density (total heat of combustion of equivalent mass of wood per unit floor area) [1,2,3,4]. In the rooms with large openings, flashover fires would not take place but fuel-controlled fires may take place[5]. Thus the effective surface area of combustibles has been included in the items of survey[6]. In addition, characteristic dimension and separation distances are sometimes needed[7,8] when we establish design fire source for initial growth period.

Inevitably, field survey of combustibles takes a lot of time and cost. However there is a possibility of increasing the effectiveness of survey if we have a practical way of survey. In this study, common combustible is examined to get the weight fraction of combustible portion, size and volume. The results are summarized to derive correlation between bulk volume (volume occupied by single combustible material) and total heat of combustion, maximum heat release rate. Using the result of this work, it would be possible to estimate the properties of burning behavior if we gather information only on size and type of combustibles, which will greatly facilitate fieldwork of survey.

2. METHODS OF SURVEY

2.1 Range of Examination

The survey was made on the combustible items that commonly exist in built environment. Considering the potential use for merchandise occupancy, the items are examined together with their packing materials as they are in sale.

2.2 Methods of Measurements

As shown in Figure 1, characteristic dimension were measured as width, depth and height if the item shape is close to rectangular-parallelepiped. For cylindrical and spherical items, diameter and height were measured. For irregular-shaped items, outer dimension were recorded in order to represent bulk volume in actual state.

The weight of each item was measured after it was decomposed into wrapping, package and contents. Then weight of constituent materials was measured for cellulose (denoted by symbol *c* hereafter), soft plastics (*sp*), hard plastics (*hp*), textile (*tx*) and non-combustibles (*n*). For the case of complex items, some of the sample items were broken into pieces in order to measure weight fraction. Figure 2 shows an example.

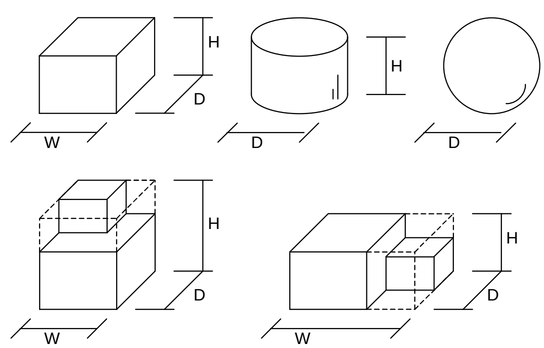

Figure 1 Definition of characteristic dimension of combustible items

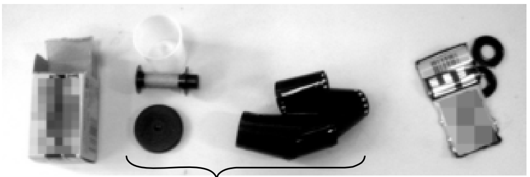

Figure 2 An example of decomposition of items into pieces (photo film package)

2.3 Estimation of Burning Parameters

By using dimensions and weight measured as above, THR (Total Heat Release) per unit weight and maximum HRR (Heat Release Rate) per unit surface area were estimated. As to THR, average value was calculated using the weight of each constituent

$$\Delta H = \sum_k w_k \Delta H_k / \sum_k w_k \, , \qquad (1)$$

where w_k is the weight of each constituent [kg]、ΔH_k is the corresponding unit heat of combustion [MJ/kg]. Summation for subscript k (= c, sp, hp, tx, n) denotes the sum over all the constituents.

As to the HRR per unit surface area, area fraction of each constituent ρ_k was estimated by

$$a_k = \frac{(w_k / \rho_k)^{2/3}}{\sum_k (w_k / \rho_k)^{2/3}} \text{ [m}^2\text{/m}^2\text{].} \qquad (2)$$

Then the HRR was averaged with a_k as

$$q_0 = \sum_k q_k a_k \qquad (3)$$

Other than THR and HRR, we should consider specific heat c_p[kJ/kg.K], heat of decomposition L_v[MJ/kg], decomposition (melting) temperature T_m [^{o}C]. These values were estimated by averaging with weight as

$$\overline{c_p} = \sum_k w_k c_{p,k} / \sum_k w_k \qquad (4)$$

$$\overline{L_v} = \sum_k w_k L_{v,k} / \sum_k w_k \qquad (5)$$

$$\overline{T_m} = \sum_k w_k T_{m,k} / \sum_k w_k \qquad (6)$$

The values for each constituent are listed Table 1, which were derived by averaging common values in several textbooks.

Table 1 Characteristics values of constituents[9-19]

	c	*sp*	*hp*	*tx*
heat of combustion ΔH_k [MJ/kg]	17.6	38.7	27.7	19.6
heat of decomposition $L_{v,k}$ [MJ/kg]	3.36	1.34	2.16	2.08
density ρ_k [kg/m^3]	413	34	1367	215
specific heat $c_{p,k}$ [kJ/kg.K]	1.37	1.59	1.37	1.43
decomposition temperature $T_{m,k}$ [^{o}C]	283	332	366	409
heat release rate per unit area q_k[kW/m^2]	132	413	697	160

3. SURVEY RESULTS

The examined items were categorized into 5 groups (textiles, large solid items, dairy goods, food, trash) as shown in Table 2. Some of the groups are classified further. The total number of examined items was 1852. Among them, 510 items were decomposed into constituents and measured directly. When direct measurement is not possible, the weight fraction was evaluated by published data. For example, plastic weight fraction of household appliances were taken by 45% for refrigerators, 13% for air conditioners, 36% for spin washers, 11% for micro-ovens, 63% for vacuum cleaners, 34% for other household appliances. As to audio/ visual equipments, weight fraction was taken by 22% for television sets, 32% for video recorders, 27% for other audio/visual eqipments[20,21, 22].

Table 2 Number of Examined Items

group / type	examples	number of items
textiles		
Clothing	wares, trousers, socks, gloves, mufflers	11 (11)
Bedding	bedding, mattress, cushion, pillow, curtain	23 (22)
large solid items		
Furniture	large furniture	13 (1)
electric appliances (household)	heating appliances, spin washer, ventilation fan, vacuum cleaner, massage equipment	873 (1)
(computers)	personal computer, printer	229 (12)
(audio/visual)	television sets, radio, camera, VTR	175 (1)
daily goods		
accessories	handbag, tie-pin, umbrella, slipper	83 (36)
dishes	dishes, lacquer ware, lunch box, casserole, chopsticks	42 (42)
cooking goods	cups, saucers	56 (52)
toys	toys, dolls, game machine	49 (47)
stationary	writing paper, binder, pens, pocket calculator, PC software, pen case	66 (61)
miscellaneous goods	miscellaneous goods	144 (136)
food		
dry food	packed dry food, cup noodle, snacks	47 (47)
medical goods	medicine, sticking plaster, mask	31 (31)
Trash	paper trash, corrugated cardboard, PET bottles	10 (10)
Total		1852 (510)

Numbers in parentheses correspond with the numbers with weight fraction measurements.

3.1 Textiles (Clothing, Bed ware)

This group includes two categories (clothing, bed wares). Clothing includes wares, trousers, socks, gloves, mufflers and so on. Bed wares include bedding materials such as sheets, mattress, pillows, cushions and so on.

The sample weight is correlated with bulk volume. The results are shown Figures 3 and 4 (first graph in each figure). If the density of items is invariant with size, weight may be proportional to bulk volume. However, measured results show that power is less than unity. This tendency implies that large items contains larger void than small items.

Similar tendency is shown in the correlation between bulk volume and surface area (second graph). If the item shape is close to sphere or cube, surface area is proportional to (2/3)-power of bulk volume. In contrast, surface area of flat and long items would be proportional to bulk volume (power is close to unity). Measured results show that the power is approximately 0.6. This tendency reflects the fact that small items tend to be flat and/or long, while large items are sphere- or cube-like shape because they are likely to be folded.

The results of THR and HRR estimation are shown in third and fourth graphs. As to clothing, THR and HRR values are 19.1 MJ/kg and 157 kW/m^2. These values are almost identical with the intrinsic values of textiles. As to bed wares, THR and HRR values are a bit larger than clothing.

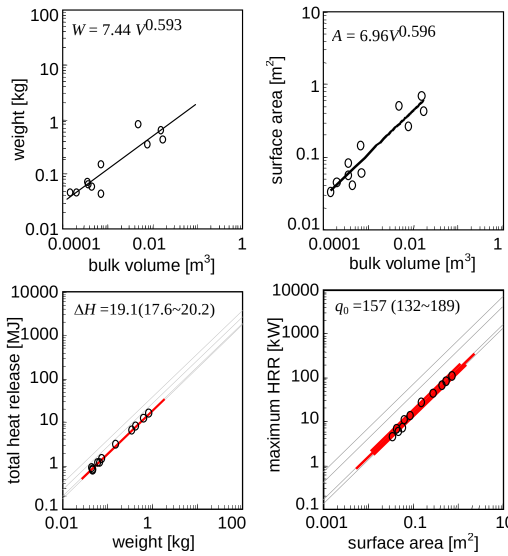

Figure 3 Survey Results (Clothing)

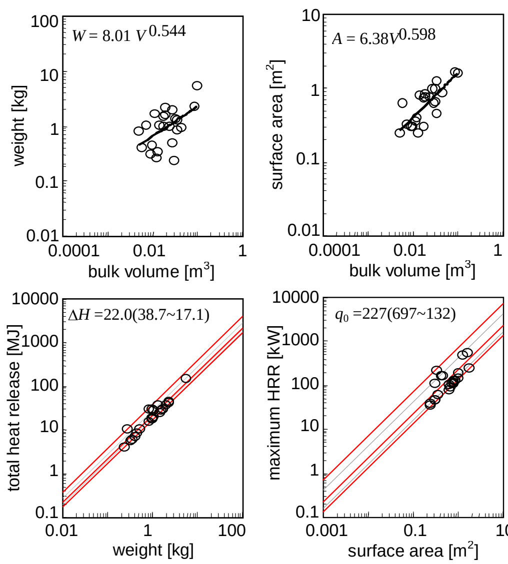

Figure 4 Survey Results (Bed ware)

3.2 Large Solid Items (Furniture, Electric Appliances)

Furniture and electric appliances are classified into this group. The results for furniture is shown in Figure 5. At this moment, number of samples is not enough for the wide range of variation of furniture types. In addition, most of the data are taken from catalog values. Thus the data may be inaccurate. However, clear tendency exists on weight and surface area of items. THR values are not so large compared with textiles. In contrast, HRR values are large because this group contains more plastic materials than textiles.

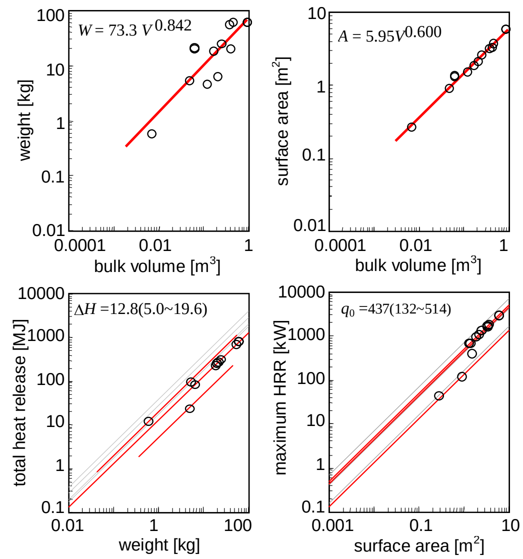

Figure 5 Survey Results (Furniture)

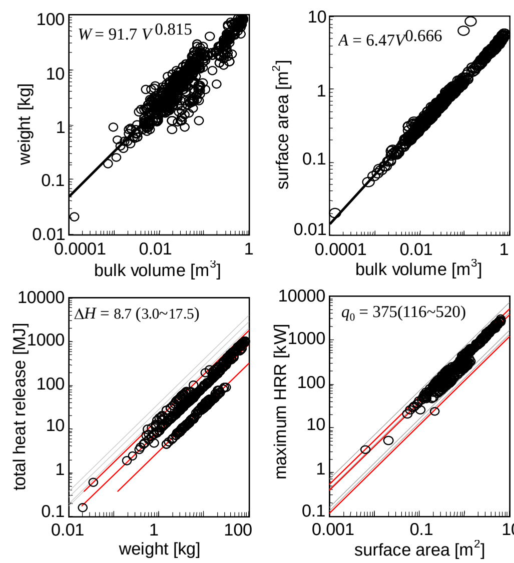

Figure 6 Survey Results (electric appliances / household)

As to electric appliances, data were further classified into three sub-groups (household, audio/visual, personal computers). Figure 6 shows the results for household appliances. Also in this case, most data were taken from catalog values. The tendency is again clear and similar to furniture.

3.3 Dairy Goods (Accessories, Dishes, Kitchen Goods, Toys, Stationeries and Miscellaneous Goods)

The group "Dairy Goods" contains 6 categories (accessories, dishes, kitchen goods, toys, stationeries and miscellaneous goods). The results for accessories, kitchen goods, stationeries and miscellaneous goods will be described in the followings.

Accessories contain relatively small goods such as handbags, tie-pin, umbrella, shoes, slippers. The results are shown in Figure 7. The weight of items per unit bulk volume is about twice of textiles. Surface area is about 70% of textiles. As to THR and HRR values, variation by composition is considerable. The upper bounds of THR and HRR are given by bags, shoes and tiepins, while umbrella gives lower bound.

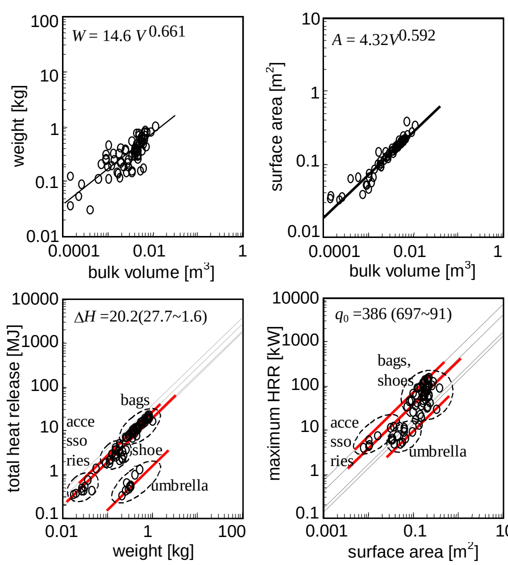

Figure 7 Survey Results (Accessories)

The results of kitchen goods are shown in Figure 8. This category contains various kitchen wares that are made of plastics, wood and metals. The variation of weight and surface area are moderate. However the variation of THR and HRR is considerable depending on the type of materials.

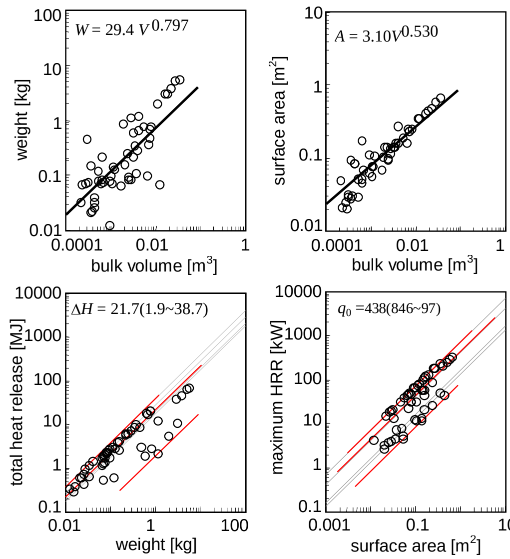

Figure 8 Survey Results (Kitchen Goods)

The results of stationary is shown in Figure 9. This category contains a variation of stationeries such as pencils, notes, file binders, pen cases and so on. Thus the scatter in weight and surface area is considerable, especially in case of small items. The variation of THR and HRR is not significant. They are within the bound of cellulose and plastic materials.

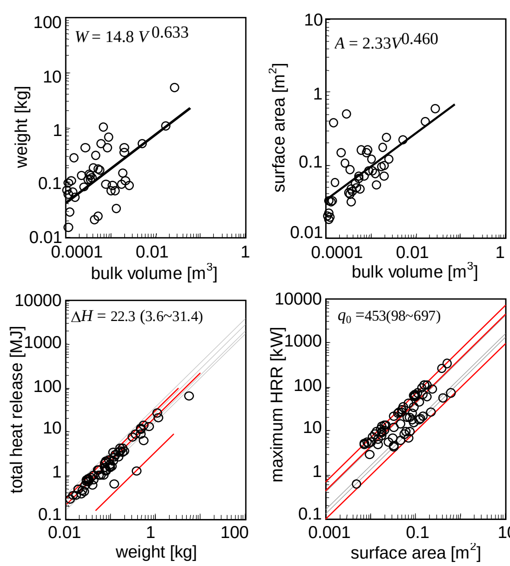

Figure 9 Survey Results (Stationary)

The results of miscellaneous goods are shown in Figure 10. Reflecting the wide variation of goods, variation of weight is in the order of 1 or 2 magnitudes. However, the variation of surface area, THR and HRR are relatively small.

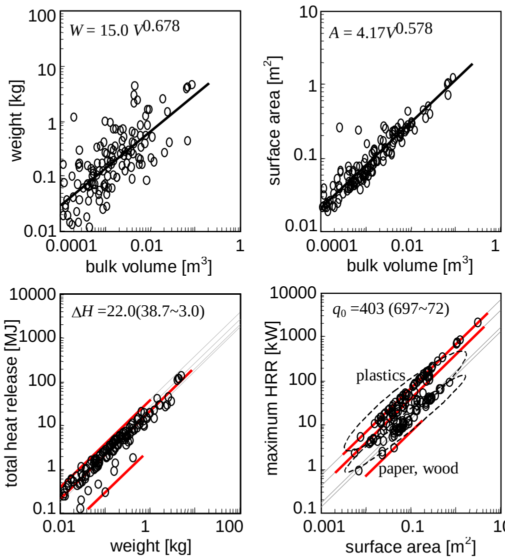

Figure 10 Survey Results (Miscellaneous Goods)

3.4 Dry Foods and Medical Goods

Dry foods and medical goods alone are not a significant threat of fire. However, their packages are likely to burn easily. Figure 11 shows the results of dry food. This category contains packed dry food and snacks. As to the heat of combustion, net calorific value shown in package was added. As is shown, the weight is about half of dairy goods. THR and HRR are non-negligible values. THR is about 3/4, HRR is 1/4 of dairy goods.

Medical goods contain medicine and surgical materials. As shown in Figure 12, THR and HRR values are non-negligible also in case of medical goods.

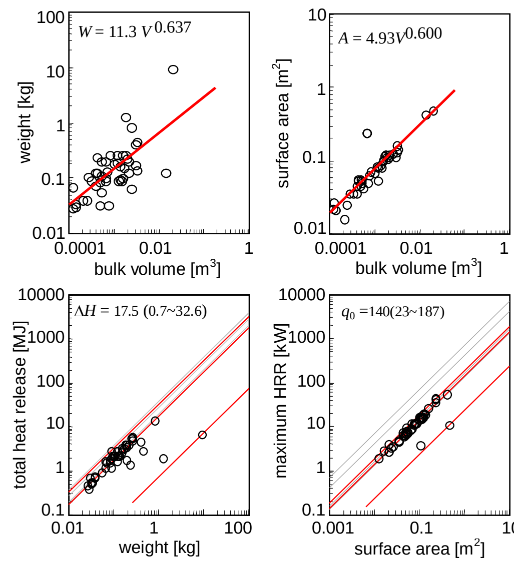

Figure 11 Survey Results (Dry Foods)

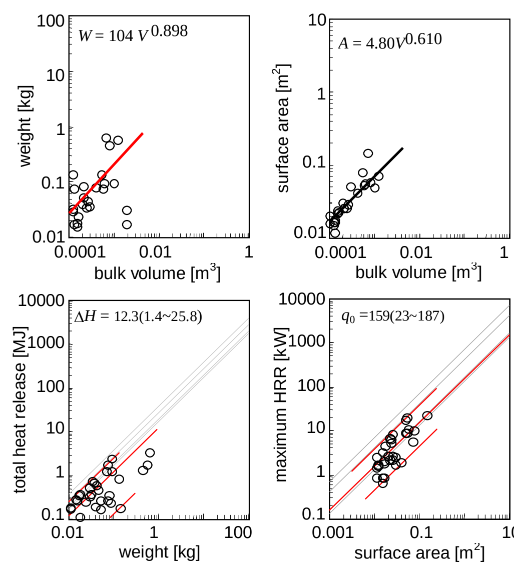

Figure 12 Survey Results (Medical Goods)

3.5 Trash

As to trash, ten samples were examined. All were in plastic bags of various sizes. Unlike other categories, weight is in proportion with bulk volume. THR values are in the range of 17.6 to 38.7 MJ/kg depending on the type of trash.

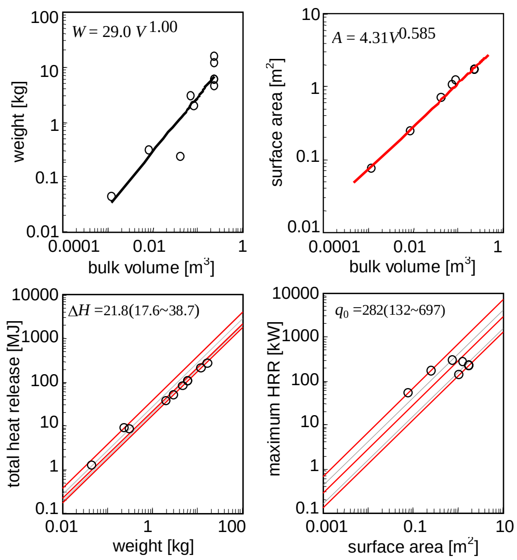

Figure 13 Survey Results (Trash)

4 CHARACTERISTIC VALUES FOR COMBUSTIBLE GROUPS

4.1 Weight Fraction of Constituents

The measured results of weight fraction of constituents are summarized in Figure 14. As to the textiles (clothing and bed ware), cellulose and textile materials are dominant. Plastic fraction is small especially in case of clothing. As to large solid items (furniture, electric appliances), about 30% is made of cellulose, 30- 40% is made of plastics. The rest is made of non-combustibles such as metal and glass. As to dairy goods (accessories, dishes, kitchen goods, toys, stationeries and miscellaneous goods), 30% is made of cellulose. Plastic fraction is 40-60%. As to food (dry food, medical goods), combustible fraction is relatively small (10-35%). Trash is composed of either cellulose or plastics.

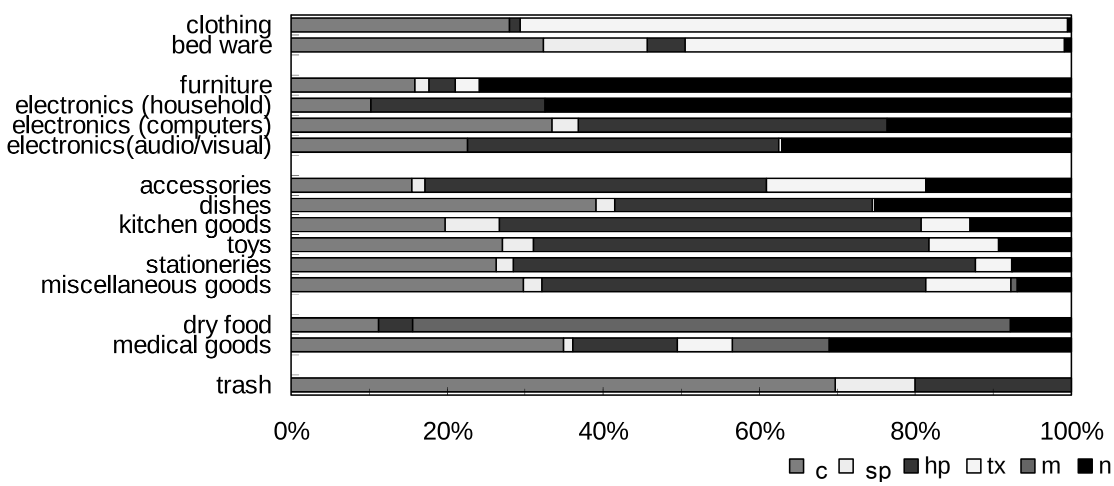

Figure 14 Weight Fraction of Constituents (c=cellulose, sp = soft plastics, hp = hard plastics, tx = textile materials, m = miscellaneous materials, n = non-combustible materials)

4.2 Summary of Characteristic Values

All the correlation formula is summarized in Table 3, for all the categories of combustibles. In practice, if we have information on the bulk volume of typical combustibles (V [m^3]) by some way (typically by field survey), it is possible to estimate the weight, surface area of combustibles for each type of common combustibles. It is surprising that weight of most categories are correlated by 2/3 of bulk volume and that surface area are correlated by 3/5 of bulk volume.

After we got weight and/or surface area of combustibles, we can estimate heat of combustion and heat release rate using Figures 15 and 16. Note that these values are still scattered around average. Maximum values correspond with the items made of plastics only. Minimum values correspond with composite items. If we have information on material type (cellulose dominant, plastic dominant, mixture and so on) through site investigation, the accuracy of survey would be improved considerably.

As an example of use of these figures, THR and HRR of items with 0.01m^2 volume are calculated for all the groups. The results are shown in Figure 17. Large HRR values are assigned to furniture, toys, stationary and dairy goods. Large THR values are for household appliances (PC), dishes, medicine, furniture, electronic appliances (household, audio/visual) and cooking goods.

Table 3 Summaries of Characteristic Values

	weight * [kg]	surface area * [m^2]	ΔH ** [MJ/kg]	q_o ** [kW/m^2]	c_p [kJ/kg.K]	L_m [MJ/kg]	T_m [^{o}C]
clothing	7.44 $V^{0.593}$	6.96 $V^{0.596}$	19.1 (20.2, 17.6)	157 (189, 132)	1.41	2.43	373
bed ware	8.01 $V^{0.544}$	6.38 $V^{0.598}$	22.0 (38.7, 17.1)	227 (697,132)	1.42	2.34	356
furniture	73.3 $V^{0.842}$	5.95 $V^{0.600}$	12.8 (19.6, 5.0)	437 (514, 132)	0.95	1.22	359
electronics							
(household)	91.7 $V^{0.815}$	6.47 $V^{0.666}$	8.7 (17.5, 3.0)	375 (520, 116)	0.65	0.68	366
(computers)	101 $V^{0.700}$	4.47 $V^{0.553}$	8.7 (26.5, 3.9)	322 (648, 191)	0.77	0.76	362
(audio/visual)	45.7 $V^{0.679}$	5.43 $V^{0.630}$	7.7 (16.1,7.5)	320 (443, 201)	0.72	0.62	365
accessories	14.6 $V^{0.661}$	4.32 $V^{0.592}$	20.2 (27.7, 1.6)	386 (697, 91)	1.22	1.87	358
dishes	65.0 $V^{0.830}$	4.82 $V^{0.592}$	17.0 (36.1, 1.4)	325 (697, 23)	1.23	2.07	313
kitchen goods	29.4 $V^{0.797}$	3.10 $V^{0.530}$	21.7 (38.7, 1.9)	438 (697, 84)	1.27	1.98	342
toys	7.92 $V^{0.609}$	6.03 $V^{0.644}$	21.5 (38.7, 3.4)	417 (697, 126)	1.28	2.19	342
stationeries	14.8 $V^{0.633}$	2.33 $V^{0.460}$	22.3 (31.4, 3.6)	453 (697, 98)	1.32	2.19	346
misc. goods	15.0 $V^{0.678}$	4.17 $V^{0.571}$	22.0 (38.7, 3.0)	403 (697,72)	1.33	2.26	342
dry food	11.3 $V^{0.637}$	4.93 $V^{0.600}$	17.5 (32.6, 0.7)	140 (187,23)	1.43	2.07	313
medical goods	104 $V^{0.898}$	4.80 $V^{0.610}$	12.3 (25.8, 1.4)	159 (187,23)	1.38	1.63	308
trash	29.0 $V^{1.000}$	4.31 $V^{0.585}$	21.8 (38.7, 17.6)	282 (697,132)	1.39	2.91	305
total	41.2 $V^{0.728}$	4.96 $V^{0.588}$	17.0 (38.7, 0.7)	323	1.19	1.81	343

* Symbol V denotes bulk volume [m^3]. ** average (maximum, minimum)

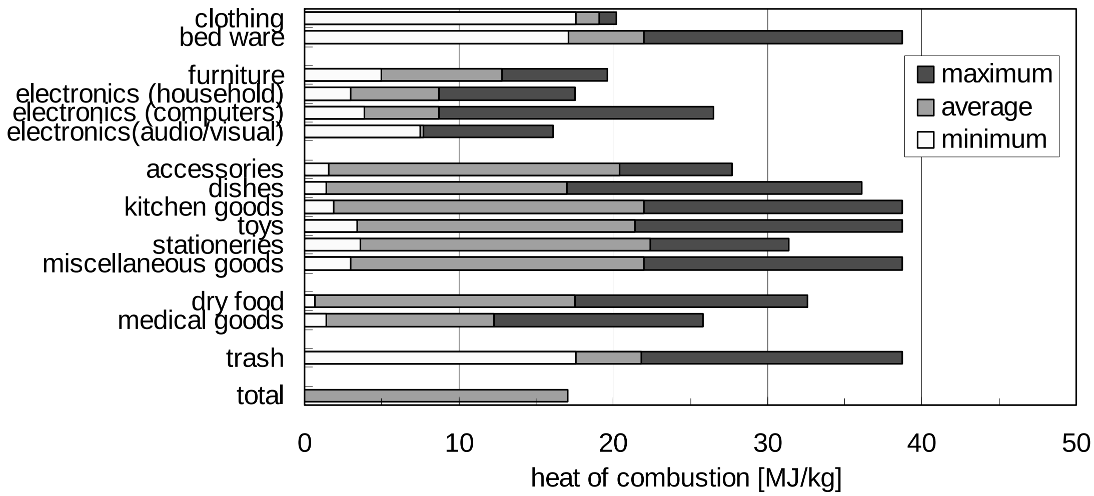

Figure 15 Heat of Combustion Values for Each Group of Combustibles

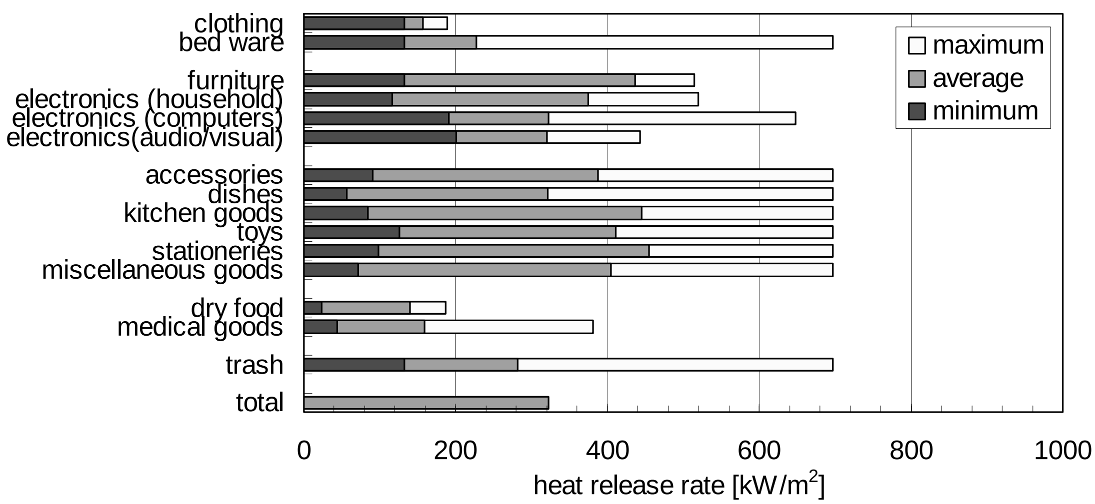

Figure 16 Heat Release Rate Values for Each Group of Combustibles

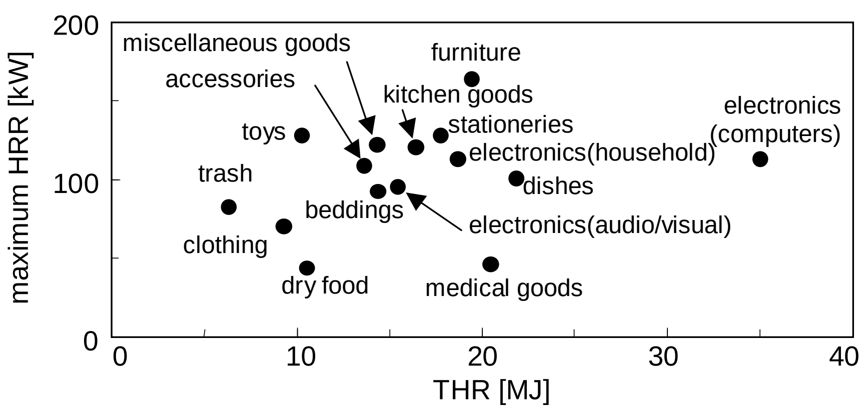

Figure 17 THR and maximum HRR values for the items with volume of $0.01m^3$

5. CONCLUSION

Characteristic dimension and weight fraction of common combustible items were measured to derive statistical correlation of burning properties. The results were summarized by 6 groups (13 categories) determined by common group names. Item weight and surface area were correlated with bulk volume for each category. Also THR and HRR were estimated by using the measured weight fraction of constituents.

Clear statistical correlations were obtained for 4 groups (textiles, large solid items and trash). In case of rest 2 groups (dairy goods, food) the correlation is just fair. However, by using the results of this study, it would be possible to make quick estimate of fire load density if we know the type and characteristic size of items.

6. FUTURE WORK PLAN

If we have information on arrangement factor (degree of reduction of surface area due to congestion), we would be able to make quick estimate of fire spread and heat release rate during initial stage if we apply appropriate fire spread models similar to wall and ceiling fire. The gathered data will be further examined if we can develop such correlations.

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