Precision of Heat Release Rate Measurement Results

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Abstract. *In this article the individual sources of errors are defined for the HRR calculations, with regard to the Single Burning Item (the SBI) test. The relative standard uncertainties of each quantity have been estimated and listed in tables together with their contribution to the combined relative uncertainty. The statistical analysis of the parameters HRR, $FIGRA_{0,2MJ}$, $FIGRA_{0,4MJ}$ and their reproducibility and repeatability standard deviations have been performed.*

Keywords: Heat release rate, fire testing, uncertainty,reproducibility, repeatability

1. Introduction

When performing fire testing, Heat Release Rate (HRR) is one of the most important quantities to determine. Rather complicated measurements are included in SBI (Single Burning Item) method for measuring HRR [1]. These data are then transformed into the FIGRA (Fire Growth Rate) value.

Dahlberg reports a relative error of 7 % for HRR measurements in the SP Industry Calorimeter when the HRR is in the range of 2 to 7 MW [2]. Enright and Fleischmann presented a relative error of 3 % for a fictive measurement of a Heptane pool fire of 374 kW [3]. The same authors later have studied the uncertainty related to the heat release rate calculation of the cone calorimeter according to the ISO 5660-1 standard [4]. Analysing their example, relative uncertainties from ±5 % to ±10 % can be obtained at heat release rates larger than approximately 50 kW/m^2. For the cone calorimeter, the relative repeatability and reproducibility standard deviations s_r/m and s_R/m are in ranges of 3-55 % and 4-87 %, respectively, for the maximum and total heat releases [5, 6]. Related to heat release measurement of room fires, Yeager has calculated the measurement uncertainty as a combination of uncertainties of gas analysis, volume flow rate ant heat production constant of oxygen consumption [7]. At heat release rates and volume flow rates typical for room fire experiments, the relative uncertainties varied from ±5 % to ±11 %.

The objective of this work was to determine the reliability of HRR measurement results when determining indexes of reaction to fire for the building products by applying the SBI test method.

2. Research and tests method

HRR determination. For the research the typical EN 13823 tests equipment has been used [1]. Equation 1 has been used for the analysis of calculating HRR using oxygen consumption principle [8].

$$HRR = \frac{E \cdot q_m \cdot \dfrac{M_{O_2}}{M_{air}} \cdot (1 - X^0_{H_2O})}{\dfrac{\alpha - 1}{X^0_{O_2}} + \dfrac{1 - \dfrac{X_{O_2}}{1 - X_{CO_2}}}{X^0_{O_2} - \dfrac{X_{O_2} \cdot (1 - X^0_{CO_2})}{1 - X_{CO_2}}}} \tag{1}$$

Where HRR - the heat release rate from the fire, kW;
E - amount of energy developed per consumed kilogram of oxygen, kJ/kg;
q_m - mass flow in exhaust duct, kg/s;
M_{O_2} - molecular weight for oxygen, g/mol;
M_{air} - molecular weight for air, g/mol;
α - expansion factor;
$X^0_{O_2}$ - mole fraction for O_2 in the ambient air, measured on dry gases;
$X^0_{CO_2}$ - mole fraction for CO_2 in the ambient air, measured on dry gases;
$X^0_{H_2O}$ - mole fraction for H_2O in the ambient air;
X_{O_2} - mole fraction for O_2 in the flue gases, measured on dry gases;
X_{CO_2} - mole fraction for CO_2 in the flue gases, measured on dry gases.

Calculation of HRR measurement uncertainty. The standard uncertainty was calculated assuming a rectangular, triangular or t-distribution. Methods used to evaluate the individual relative errors included studying the manuals and measuring drift of instruments during usage. The standard uncertainties were mainly classified as type „B". No distinction between systematic and random errors was made. All errors were regarded as random.

Round robin tests. The analysis of the reliability of the heat release rate measurement results has been based on the results of the SBI round robin test series [1, 9]. The round robin was conducted by 15 laboratories, testing 30 products in threefold.

3. Calculation and experimental research results

Table 1. HRR uncertainty (35 kW and 50 kW)

Quantity, x_i	Relative error, (%)		Relative standard uncertainty, $u(x_i)/x_i$, (%)		Relative sensitivity coefficient, $c_{r,i}$		Contribution to combined relative uncertainty of HRR measurement $c_{r,i} \cdot u(x_i)/x_i = u_i(y)$ (%)	
	35 kW	50 kW	35 kW	50 kW	35 kW	50 kW	35 kW	50 kW
q_m			2.1	2.1	1	1	2.1	2.1
X_{O_2}			0.082	0.091	-80	-54	6.6	4.9
X_{CO_2}	2.5	2.5	1.02	1.02	-0.19	-0.18	0.194	0.184
E	5	5	2.04	2.04	1	1	2.04	2.04
α	12	12	6.93	6.93	-0.019	-0.03	0.13	0.21
$X^0_{H_2O}$	165	165	67.4	67.4	-0.004	-0.004	0.269	0.269
M	1.5	1.5	0.86	0.86	1	1	0.866	0.866
Combined expanded relative standard uncertainty							14.5%	11.6%

The relative standard uncertainties of each quantity (see equation 1) were estimated and listed in table (see table 1) together with their contribution to the combined relative uncertainty. Some of the uncertainties were found to be dependent on the HRR and therefore the uncertainties were calculated for two different levels of HRR (35 kW and 50 kW). The individual errors the combined expanded uncertainty has been calculated, using a coverage factor of 2. The calculation EN 13823 standard requires 30 s averaged values and measurements are made every third second. The combined expanded relative standard uncertainty for the 30 s averages for the 35 kW level is $14.5/\sqrt{10}$ =4.6% and $11.6/\sqrt{10}$ =3.7% for 50 kW level.

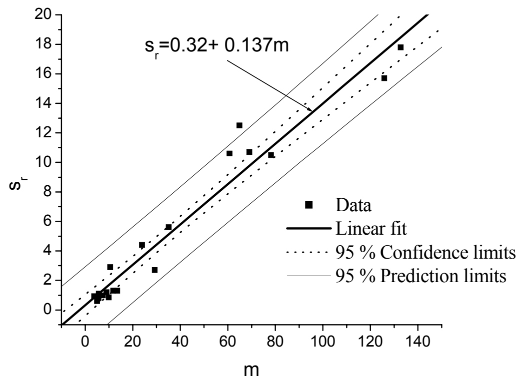

Fig. 1. s_r and m (HRR) reliance

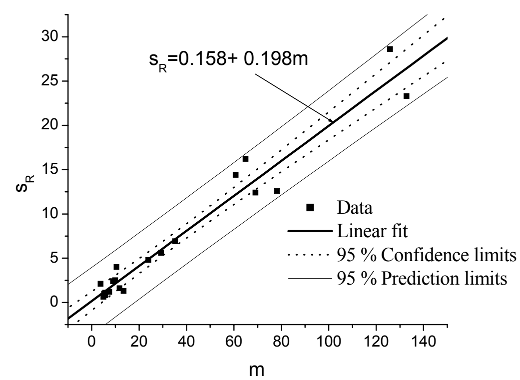

Fig. 2. s_R and m (HRR) reliance

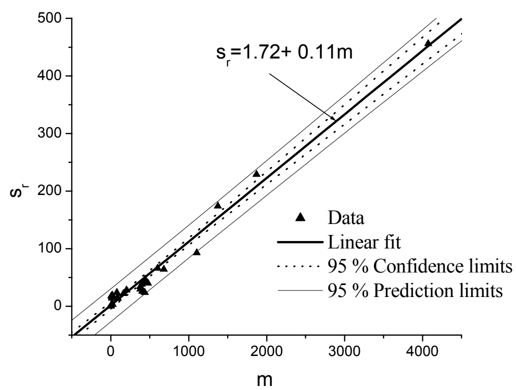

Fig. 3. s_r and m ($FIGRA_{0,2MJ}$) reliance

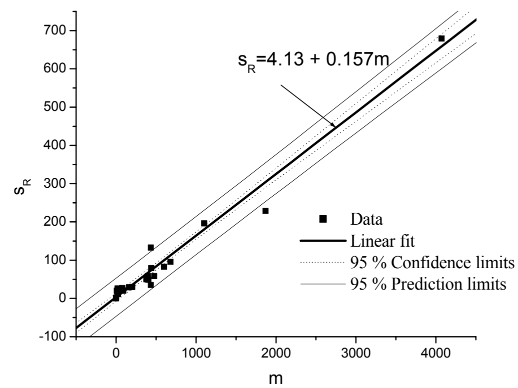

Fig. 4. s_R and m ($FIGRA_{0,2MJ}$) reliance

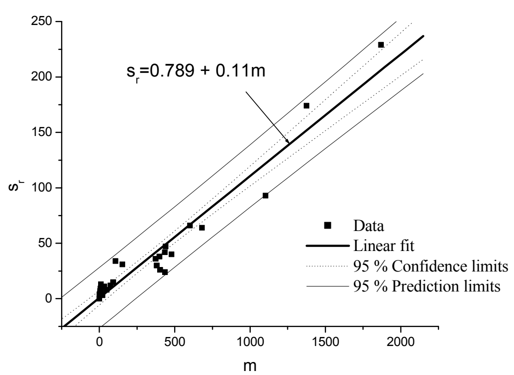

Fig. 5. s_r and m ($FIGRA_{0,4MJ}$) reliance

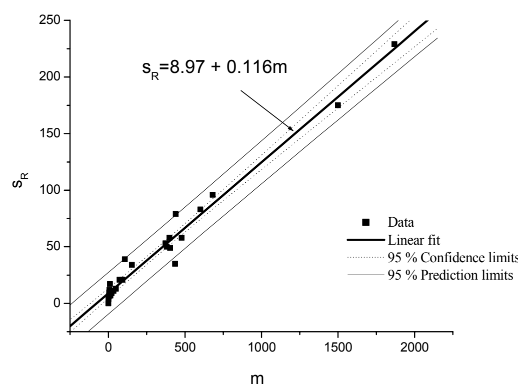

Fig. 6. s_R and m ($FIGRA_{0,4MJ}$) reliance

The analysis of the pass-fail parameters was performed. The statistical analysis of the parameters HRR, $FIGRA_{0,2MJ}$, $FIGRA_{0,4MJ}$ average values and their standard deviations for the reproducibility and repeatability was performed. The analysis was performed on s_r, s_R and m quantities reliance (see Fig. 1, 2, 3, 4, 5 and 6). Pursuant to these data linear regression equations have been calculated and linear regression lines have been obtained (see Fig. 1, 2, 3, 4, 5 and 6).

These cases indicate quite narrow limits of 95 % confidence and prediction (see Fig. 1, 2, 3, 4, 5 and 6). All calculated correlation coefficients are close to 1 and probabilities P (that R is 0) are <0.0001 in all cases. Using regression equations (see figures 1, 2, 3, 4, 5 and 6) one can carry out prediction for possible interval of s_r and s_R for the particular variable m value.

Table 2. R, s, P values.

Reliance	Correlation coefficient, R	Standard deviation, s	Probability, P
s_r ir m (HRR)	0,97783	1,19	<0,0001
s_R ir m (HRR)	0,97743	1,74	<0,0001
s_r ir m (THR=0,2MJ)	0,98933	13,6	<0,0001
s_R ir m (THR=0,2MJ)	0,98408	23,6	<0,0001
s_r ir m (THR=0,4MJ)	0,96913	13,0	<0,0001
s_R ir m (THR=0,4MJ)	0,98753	8,66	<0,0001

4. Discussion

The calculated reliability indexes of HRR measurement results are medium as compared to the reliability indexes of the other HRR determination methods.

The table 1 shows quite a high HRR uncertainty, mainly due to the O_2 uncertainty, followed by the E-factor and the mass flow in the exhaust duct. The uncertainty in the oxygen measurement depends on the instrument used and the size of the fire. HRR measurement accuracy one can increase using another type of O_2 analyser (not paramagnetic). The E-factor is independent of the experimental apparatus but depends on the fuel used. If the fuel is known then the uncertainty decreases. The uncertainty in the velocity profile in the duct and the bi-directional probe constant are the most important for the mass flow measurement. Values s_r and s_R depend on the FIGRA, HRR values. Therefore, it is important to pay attention to the measurements when HRR is high.

It is important to note that the heterogeneity of the materials has a big influence on the accuracy of HRR measurement results.

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