CONE CALORIMETER – A TOOL FOR MEASURING HEAT RELEASE RATE

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ABSTRACT

The cone calorimeter is considered the most significant bench scale instrument in fire testing. This apparatus has been adopted by the International Organization for Standardization (ISO 5660-1) for measuring heat release rate (HRR) of a sample. It has been shown that most fuels generate approximately 13.1 MJ of energy per kg of oxygen consumed. Therefore, HRR is based on the fact that the oxygen consumed during combustion is proportional to the heat released. This device analyses the combustion gases and measures the produced smoke from a test specimen that is being exposed to a certain heat flux. At least the oxygen concentration must be analyzed to calculate the released heat, but to improve the accuracy, carbon monoxide and carbon dioxide concentrations can also be analyzed.

The data collected from this bench scale real fire test can be used for fire modelling, prediction of real scale fire behaviour, pass/fail tests etc.

In this work the principle and use of this technique will be described. Since this method measures heat release rate indirectly by calculations based on oxygen consumption, the uncertainties originating from assumptions, calculations and the tested fuels will also be discussed.

Keywords: Cone calorimeter, heat release rate, oxygen consumption, heat of combustion.

1 INTRODUCTION

The cone calorimeter is a fire testing device based on the principle of oxygen consumption during combustion. This device is used by most leading fire research groups as a data source for properties of materials and as a source for input data to models when predicting fire behaviour. The cone calorimeter is considered the most significant bench scale instrument in fire testing (BABRAUSKAS, Vytenis and Peacock, Richard D., 1992). A fuel sample surface can be radiated with different heat fluxes by this device. The fuel sample ignites and burns in excess air. Amongst the results are time to ignition, mass loss, smoke amounts, gas analyses, heat release rate and other parameters related to burning properties of a fuel.

Heat release rate is defined as the mass loss rate of the material times its heat of combustion.

1.1 Early development and standardisation

The modern cone calorimeter started to take form in the early 1980's. A new technique called oxygen consumption calorimetry based oxygen concentration measurement in the flue gases had been introduced (HUGGETT, Clayton, 1980). The development of a cone calorimeter was started already in the late 1950's when similar types of measurements were started, and in the 1970's the original NBS calorimeter (National Bureau of Standards, from 1988 NIST, National Institute of Standards and Technology) was built. The early versions were based on other measurements, and with burners instead of electrical heaters they were complex and difficult to use, but had good accuracy (BABRAUSKAS, Vytenis, 1983) (BABRAUSKAS, Vytenis, 1993).

The first proposal to standardisation of cone calorimeter measurements was the ASTM P 190 in 1986. The full version was published in 1990 as the ASTM E 1354-90. The cone calorimeter method was also presented as a draft for ISO standard in 1990, and in 1993 the final form of the ISO 5660-1 was published. The latest version was revised in 2002.

2 GENERAL DESCRIPTION

2.1 Parts

The cone calorimeter consists of numerous essential parts and devices. Together these parts measure, log, set and adjust several parameters like temperatures, mass, gas flow and concentration. In Figure 1 these parts are described in a schematic picture.
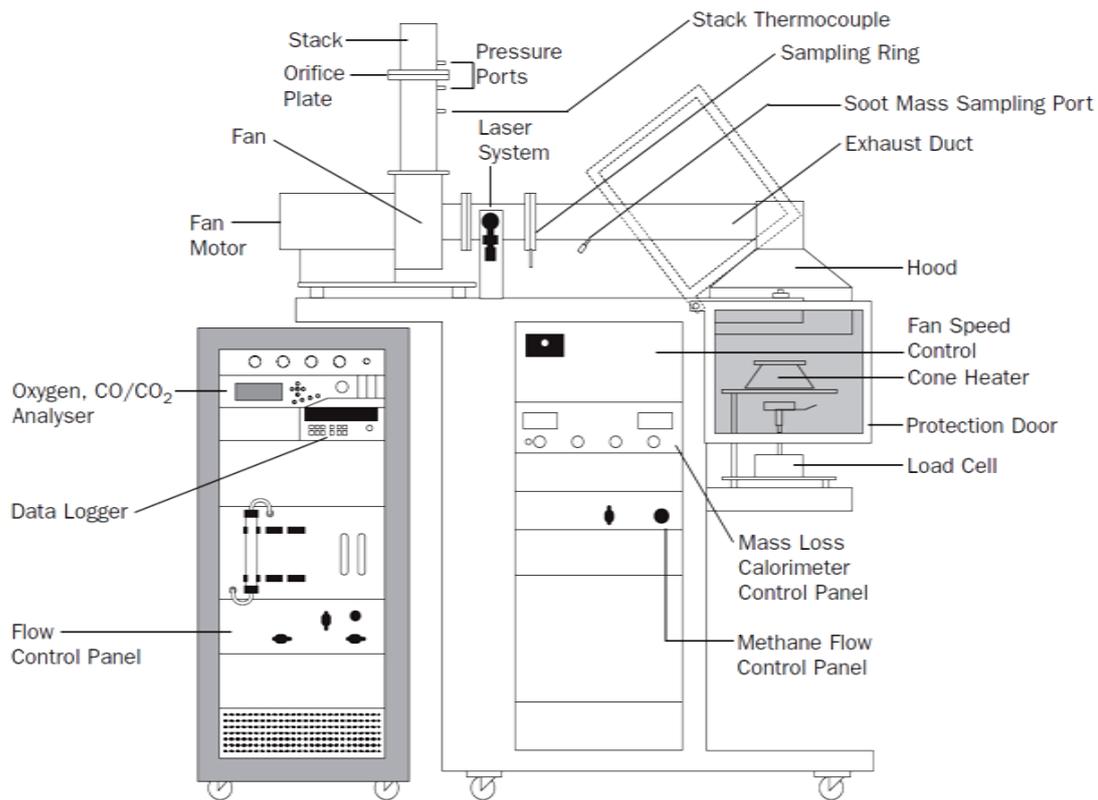
Figure 1 Schematic picture of the Cone Calorimeter. Modified from (FTT Cone Calorimeter brochure)

The specimen is placed on a metal sample holder, which is placed on the load cell. The load cell records the weight of the sample during the experiment. There are two types of sample holders. Depending on the specimen, the sample holder can have open or closed edges. If the specimen is of intumescent type (i.e. the specimen swells and forms a protective char layer), a wired grid can be fitted to keep the specimen in place when swelling occurs. The wired grid is always used when testing in horizontal position and with the edged frame sample holder.

A spark igniter is situated right above the sample surface below the cone heater. This ignites the flammable gases leaving the sample when the sample is heated. When the whole sample area is burning, the igniter is turned off and moved to the side. Prior to the experiment during calibration, a water cooled heat flux measuring device is placed at the sample surface level. The cone heater is then set to the temperature that gives the wanted heat flux at the surface of the specimen. Normally, the cone is mounted horizontally, but vertical orientation is also possible. The name of this testing apparatus originates from the shape of the heater. The heater is wound to a conical shape from an over 3 m long resistance heating wire packed in magnesium oxide refractory.

The flue gases from the burning sample are collected into the extraction hood situated directly above the heater. A flue gas fan is mounted in the flue gas line to set the flow

rate of combustion products. The gas sampling ring is situated before the fan in the flue gas line. Prior to reaching the gas analyzers, the gas sampled in the ring is first passed through two filters to remove particles, then through a cold trap and a drying agent to remove possible water. Between the gas sampling ring and the fan there is also a smoke measurement system. This measures the produced amount of smoke by a laser photometric beam.

The only analyzer needed to perform fundamental cone calorimeter experiments is the oxygen analyzer. Additional analyzers, such as carbon monoxide and carbon dioxide analyzers are usually fitted to gain better understanding of the burning process and to decrease the uncertainties in the results. For further analysis of combustion products and gas species for example a Fourier Transform Infrared spectrometer (FTIR) can be coupled through a heated line.

2.2   Relationship between oxygen consumption and heating value

Heat release rate (HRR) is calculated from the oxygen concentration in the flue gases. The heat released from a fuel has been shown to be proportional to the oxygen consumed during combustion. (HUGGETT, Clayton, 1980)

13.1 is a key value in the cone calorimeter measurements and calculations. In the study by Huggett, many fuels are shown to have almost the same value for heat of combustion. The values are close to each other even if there is a big variation in the fuel types. An average of these values is calculated to 13.1 MJ/kg O_2 (Figure 2) with an accuracy of ±5%.
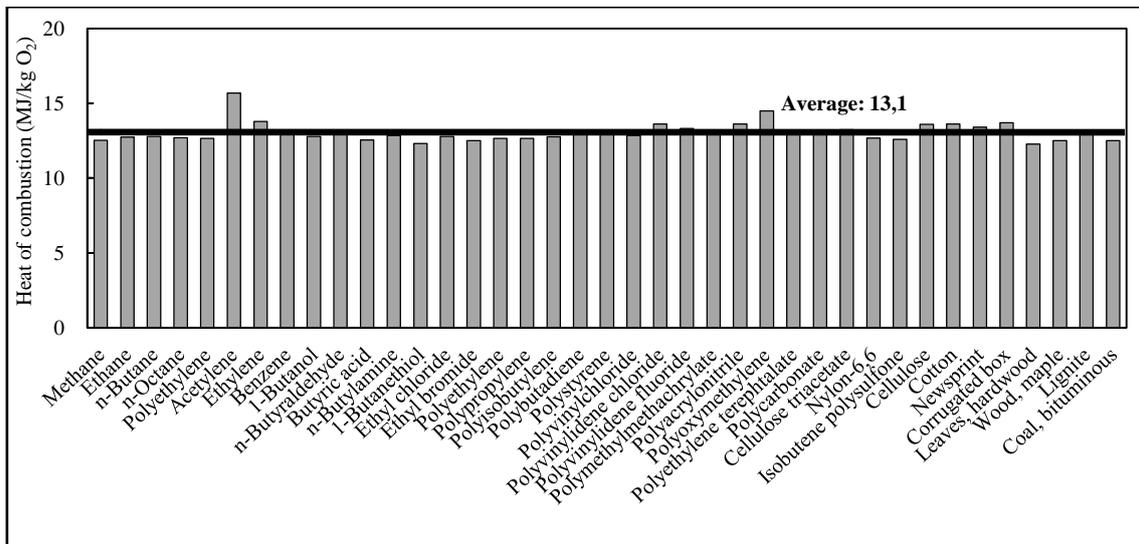

Figure 2 Heat of combustion for a range of different fuels. Data source: HUGGETT, Clayton. 1980.

The cone calorimeter software calculates the heat release rate by the following equation:

$$\dot{q} = (13.1 \cdot 10^3) \cdot 1.10C \, \frac{(0.2095 - X_{O_2})}{(1.105 - 1.5 \, X_{O_2})} \qquad \text{(Equation 1)}$$

Where $\dot{q}$ = rate of heat release (kW)

C = orifice plate coefficient ($kg^{\frac{1}{2}}m^{\frac{1}{2}}K^{\frac{1}{2}}$)

ΔP = pressure drop across the orifice plate (Pa)

T_e = gas temperature at the orifice plate (K)

X_{O_2} = measured mole fraction of O_2 in the exhaust air

If the fuel to be tested is known, the "real" value for heat of combustion can be used when performing experiments by entering this value into the cone calorimeter software. By doing this, the error in the final result is decreased.

3   PERFORMING EXPERIMENTS

Prior to performing any experiments, some daily setup and calibrations are needed. The gas analyzers and the laser smoke measurement system always stay turned on to be ready to use, without having to wait for warm-up and stabilisation, but the rest of the equipment has to be powered and set up. The filters on the gas sampling line are checked and changed if necessary. Drierite® (calcium sulphate with cobalt chloride indicator, >98% $CaSO_4$, <2% $CoCl_2$) is used as dying agent for the sample gas before it reaches the analyzer. This is also checked and, if needed, changed to fresh. While the exhaust control still is turned off the differential pressure transducer is zeroed. After this the exhaust control is turned on and the duct flow is set to 24 l/s using the flue gas fan.

3.1   Calibrations

The smoke measurement system and the gas analyzers for analyzing oxygen, carbon monoxide and carbon dioxide concentrations in the flue gases always stay turned on and are ready for use. The smoke measurement system is calibrated for zero value by completely blocking the laser beam and full range is reached by unblocking the beam. The gas analyzers are calibrated daily using nitrogen for zero level and CO/CO_2 span gas (0.85/8.5 %) for the wanted range for the CO and CO_2 analyzers. Air is used to span the O_2 analyzer to 20.95 %.

The orifice plate coefficient (device specific, see Eq.1), or the C-factor, is calibrated with a methane burner. The flow of methane is adjusted to produce approximately 5 kW. Since the value for heat of combustion for pure methane is known, and the gas analyzers are calibrated, a calibration of this type can determine the C-factor.

The sample holder should be set to a level that the sample surface is 25 mm below the cone.

Finally, the temperature of the cone must be set to produce the wanted heat flux at the sample surface. The heat flux is usually set to 25, 50, 75 or 100 kW/m^2. This is done by placing a water cooled heat flux gauge 25 mm below the cone and adjusting the cone temperature until the wanted heat flux is reached.

3.2   Measurements

The size of the standard specimen is 100 x 100 mm^2. The maximum specimen thickness allowed is 50 mm. The sample is wrapped in aluminium foil so that only the top surface is being radiated by the heat from the conical heater. The sides of the sample should not be exposed to the radiative heat.

Before the spark igniter is placed in position above the sample surface and the actual burning test is started, baseline data is collected for 60 seconds. The experimental data is then measured from this baseline.

4   INTERPRETATION OF RESULTS

The results from a cone calorimeter experiment include a range of parameters and data types that can be used for several different purposes, for example:

- Fire modelling
- Prediction of real scale fire behaviour
- Ranking of products by fire performance
- Pass/fail tests when developing new materials and products

Parts of the results from an experiment with a 19 mm thick wooden sample are graphically shown in Figure 3. In addition to these, several average and peak values are calculated and registered. Time to ignition, peak heat release rate, heat release rate after certain user defined times, total heat release (THR, Eq.2), mass loss and average effective heat of combustion are thermal parameters logged during the experiment. Examples of logged smoke parameters are total smoke released (TSR, Eq. 3), CO and CO_2 yields. CO and smoke are typically results from incomplete combustion and can be wanted products, if the burning process is disturbed by flame retardants.
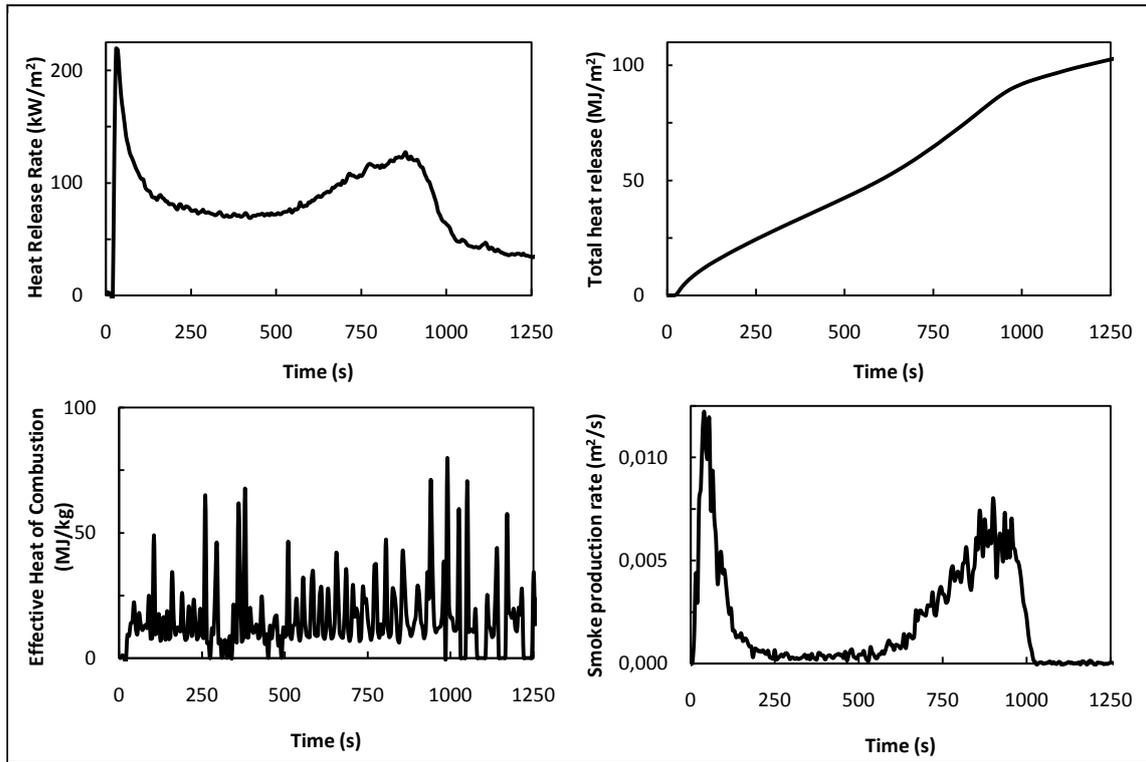
Figure 3 Examples of results from experiment with 19 mm thick wood sample at 50 kW/m^2. Top left: Heat release rate vs. time. Top right: Total heat release (cumulative) vs. time. Bottom left: Effective heat of combustion vs. time. Bottom right: Smoke production rate vs. time.

$$THR = \int_0^\infty Q(t)\, dt \quad \text{(Equation 2)}$$

$$TSR = \int_{t=0}^{t\infty} S_R \, dt \quad \text{(Equation 3)}$$

Figure 3 consists of four graphs. These are examples of results from a cone calorimeter experiment. In the top left HRR graph two peaks can be seen. The first peak is the higher and comes directly after ignition. As the heat release rate is proportional to the oxygen consumed, this means that a lot of oxygen is consumed immediately after ignition and here the peak heat release rate is then found. The second peak around 800-900 seconds appears when the surface starts to break up and oxygen reaches the inner parts of the sample and starts to burn more efficiently. The peaks and the form of the heat release rate graph follow the peaks and the form of the smoke production graph (bottom right) very well.

The total heat release (THR) curve in Figure 3 (top right graph) increases almost linearly until 900 seconds, when the second peak in the heat release rate (HRR) curve starts to decrease. This is also explained by Equation 2.

Sample thickness is another important parameter. In order to be able to produce comparable results, the samples have to have the same thickness, as shown in Figure 4.
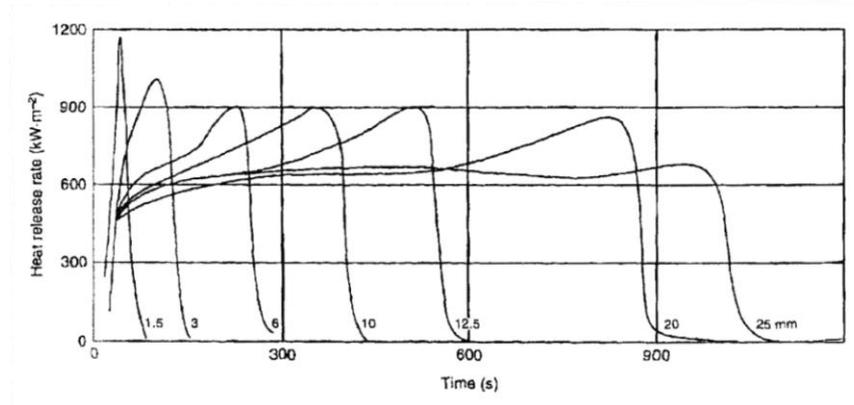

Figure 4 HRR for PMMA for thicknesses between 1.5 and 25 mm. From (SHARTEL, B. and Hull, T. R., 2007)

4.1   Sources of errors

Heat release rate cannot be directly measured. It has to be calculated from several other measurements, and as a consequence, it includes some errors and assumptions. As mentioned above in section 2.2, the error in the value for the heat of combustion can be up to 5% (HUGGETT, Clayton, 1980). Zhao and Dembsey did an extensive study on measurement uncertainty for the cone calorimeter (ZHAO, Lei and Dembsey, Nicholas A., 2008). They concluded that the relative uncertainty of HRR decreases as HRR increases. The relative error when firing methane is "approximately 20-30% for 1 kW fires, 10% for 3 kW fires and less than 10% for 5 kW fires". The uncertainties for HRR measurements are considered reasonable. Enright and Fleischmann also studied the assumptions and uncertainties in the cone calorimeter apparatus and measurement (ENRIGHT, Patrick A. and Fleischmann, Charles M., 1999). If the fuel is known or if additional analyzers, such as H_2O, CO and CO_2 analyzers, besides the required oxygen analyzer, are used, it decreases the uncertainties. The uncertainty of the calculations is very strongly coupled with the oxygen analyzer accuracy.

5   CONCLUSIONS

The cone calorimeter is a key tool fire research. The accuracy of the results from cone calorimeter experiments mainly depend on the accuracy of the oxygen analyzer, since it uses the oxygen consumption principle. The results can be used in models for up-scaling experiments and in fire testing when developing new materials. Fire hazard and development can also be predicted by cone calorimeter tests.

6   ACKNOWLEDGEMENT

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