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Physical fire tests and importance of the oxygen consumption calorimetry

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Abstract

In carrying out physical tests in fire research, there are bench-scale tests, intermediate scale tests, full-scale burning tests, and real-scale tests. These tests are established for different reasons and must account for repeatability and reproducibility. Oxygen consumption calorimetry is the most important apparatus and must be installed properly. The heat release rates in burning combustibles can be measured by monitoring the transient oxygen concentrations with smoke collected under an exhaust hood with a proper fan-duct system. This equipment can support high-quality fire research and carry out appropriate hazard assessment on developing fire-safe products. As prohibitive resources are required and causing environmental challenges, collaboration among different places on handling these full-scale burning tests is desired.

1. Introduction

Most part of this paper came from [1] the 18th Strait Forum - Straits Integrated Fire Protection and Emergency Development, held on 13-15 June 2026 in Sanming, Fujian, China, as in Appendix A. There are some parts on the recent news on the big fires enquires [2-4].

- The number of fires appears to increase
  - The Big Garley Building Fire 1996 [5].
- Big fire for 44 hours, November, 2025 [2-4].
  - Still burning big at night
  - After

Further, many new materials such as sandwich panels are used for thermal and sound insulation partitions.

- Accidental fires in double-deck buses made of sandwich panels are good examples in demonstrating the potential hazard.
  - Sandwich Panel
  - Bus Fire: Burnt completely within 10 minutes

Need combustibility data for combustible products.

Fire behaviour of building materials and contents should be assessed by appropriate tests.

Useful risk parameters such as heat release rate can then be compiled for hazard assessment.

2. Fire Tests and Scenarios

Scales:

- Bench-scale
- Medium-scale
- Full-scale
- Real-scale

Fire tests:

- Standard fire tests: products development, rules & regulations, standardized procedures, repeatability & reproducibility.
- Repeatability: Different tests at same place
- Reproducibility: Difference places
- Research and Development

Why carry out standard fire tests?

- meeting a regulatory requirement
- demonstrating that a product has adequate fire safety performance

How to select the fire test methods?

- the product and its end-use
- the performance requirements
- regulatory requirements

There are at least 3 stages of a fire.

Tests were set up for different stages of a fire: Initiation, Growth, Development, Decay, Steady Burning.

Different of standard Fire Test:

- Ease of ignition - How readily will a material ignite? to what kind of ignition source? a cigarette, a match, a large open flame?
- Flame spread - How rapidly will fire spread across a material surface? Horizontal, upward, downward, across a ceiling?
- Heat release rate - How much heat is released? How quickly?
- Fire endurance - How rapidly will fire penetrate a wall, floor, or ceiling, or other barrier (fire penetration)?
- Ease of extinction - How easily will the fire to out?
- Smoke release - How much smoke is released? How quickly?
- Toxic gas evolution - How potent and how rapidly are toxic gases released? Are they irritating? Are they corrosive?

Standard Tests Overview:

- Non-combustibility: BS476 Part 4 [6].
- Ignitability: BS476 Part 5 [6].
- Fire Propagation Test: BS476 Part 6 [6].
- Surface Spread of Flame Test for Materials: BS476 Part 7 [6].
- Fire Resistance Furnace: BS476 Part 8 [6].
- NBS Smoke Density Test: NBS Chamber is used to determine the specific optical density (Ds) of smoke generated by solid materials within a closed chamber due to flaming and/or non-flaming combustion [7].
- Ease of Extinction: Limiting Oxygen Index (Critical Oxygen Index). (ASTM D 2863-91, ISO 4589-1984) [8].

Medium-scale Tests:

- BS EN 13823 on Single Burning Item SBI [9].
    - A new standard approved by the European Committee for Standardization (CEN) in 2001.
    - British standard since 2002.
    - The test simulates a fire originating from a single burning item in the corner of a room and growing within that room to flashover.
- Japanese Reduced Model Box RMB [10].
    - Established in 1980's as a 1/3 scaled model of ISO 9705 [11].

Full-scale test:

- ISO 9705 [11]:
    - Measurements: Heat release rate, Time to flashover (if any), Temperature, Flame spread rate.

Scenarios: Ignition as an example

- Ignition should be tested for assessing whether the material is easy to start burning.
- Bench-Scale test.
    - BS 476 Part 5: 10cm by 10cm sample.

Now Batteries!

An accidental fire started from igniting a small heat source might lead to hazardous consequences.

3. Heat Release Rate and Oxygen Consumption Principle

Heat Release Rate as an Input Parameter

- How big is a fire?
- Answer: Heat release rate!
- One of the most important parameters that can be used to characterize an unwanted fire is the rate of heat release (Parker and Babrauskas) [12,13].

Heat release rate would give:

- an indication of the size of the fire,
- the rate of fire growth, and consequently the release of smoke and toxic gases, (such as sizing of smoke exhaust system)
- the time available for escape or suppression,
- the types of suppressive action that are likely to be effective, and
- other attributes that define the fire hazard.

Additional points:

- The heat release rate of burning materials is believed to be the basic element in understanding how big is the fire.
- Different values were used by the designers in the past [14]:
  - Terminal hall: up to 7 MW;
  - Shopping mall: 5 MW;
  - Atrium: up to 7 MW;
  - Train compartment: 1 MW.
- Depends on the fact that the heat release of organic materials per unit of oxygen consumed are approximately the same, about 13.1 (± 5%) MJ per kg of oxygen consumed [12,13] for most 'fuel' in fires.
- All these products involve the breaking of C-C and C-H bonds (which release approximately the same amount of energy) with the formation of CO_2 and H_2O.
- Comparison with the CO_2 production method:
  - Fuel + Air → Product + Heat.
  - Heat/[O_2] ~ Constant!
- Determine the amount of oxygen consumed:
  - Air flow rate,
  - Oxygen level before and after the combustion,
  - Temperature.
- Hence, the measurement of the precise concentration of oxygen in the exhaust duct and the volumetric flow of air give the rate of oxygen consumption.
- Instrument:
  - Air flow rate,
  - Temperature,
  - Oxygen level.
- Exhaust Hood with fan + duct.

Key element: Duct Section + Oxygen Analyzer

- Basic principle:
  - Consideration for complete combustion, a constant E = 13.1 MJ/kg of O_2 consumed [12,13] will be used as default value if the fuel is unknown.
  - $\dot{q} = E (\dot{m}^0_{O_2} - \dot{m}_{O_2})$
  - where $\dot{m}^0_{O_2}$ and $\dot{m}_{O_2}$ are oxygen mass flow rates in the intake and exhaust parts respectively.
- Correction might be necessary by measuring other incomplete combustion products (CO, Soot, etc.):
  - CO (about 17.7 MJ/kg of O_2 consumed),
  - Soot (about 12.3 MJ/kg of O_2 consumed).
- Equations were derived based on mass balancing:
  - Inert gases (most is N_2) conservation;
- Oxygen depletion factor and expansion factor might be used to relate intake and exhaust gases;
- Open system and closed system (controlled atmosphere).
- Equations might be derived under the following conditions:
  - only O_2 is measured;
  - only O_2 and CO_2 are measured;
  - only O_2 and CO are measured;
  - O_2, CO_2 and CO are measured;
  - O_2, CO_2, CO and H_2O are measured;
  - O_2, CO_2, CO, H_2O and soot are all measured.

A summary is shown in literature [15].

4. Scaling

- Bench-Scale
- Medium-Scale
- Full-Scale
- Real-Scale:
  - No standard.
  - Easy to mislead in fire investigation if the conditions are different, or without serious experimentation [4]!
  - R & R again!

Bench-scale:

- This can be assessed by a bench-scale cone calorimeter.

Building and Fire Research Laboratory:

- CFR Cone (2007),
- Parker: Oxygen consumption (2005) [12,13],
- PolyU-BSE (1994).

Old BSE Calorimeter in 1990s

BSE Calorimeter

- Cone with humidity cabin for controlling environment!

New iCone.

Medium-scale:

- Intermediate scale tests such as the furniture calorimeter [16] and single burning item (SBI) [8,9] are useful.

Full-scale:

- Further, the new ISO room-corner fire test is a full-scale burning test to measure fire spread, heat release rate and time to flashover.
- Playing with fire, Calibrating 10 MW calorimeter.
- INDUSTRY Calorimeter: at SP, Sweden.
- Swedish Industry Calorimeter.
- Factory Mutual USA. ("Hazard Calculations", SFPE handbook of fire protection engineering. Quincy, Mass.: National Fire Protection Association; Bethesda, Md.: Society of Fire Protection Engineers, 3rd ed. (2002)) [14].
- A big Exhaust Hood
  - Such a full-scale burning facility should be developed.
  - But very difficult to calibrate.
  - Easy to be challenged, if not installed properly [4]!

Selection of site for full-scale burning test:

- Away from urban area
- Environmental problem
- Transportation to the site
- Water, electricity, heating supplies
- Cost

A site is needed for full-scale burning test! The one at Sanming, as in Fig.1 might be appropriate, but not sure on good collaboration works.

(a) Duct

(b) The Hood

(c) The Site

Fig.1: Exhaust Hood of 50 MW at Sanming

5. Conclusion

- Starting flame was small before!
- New large ignition sources now!
- Different ignition sources.
- Ignition source (Waste basket) looks Better?
- Differences between Battery Fire and Normal Accidental Fire
- New Challenges on Battery Fire (Li-ion)
- More Useful Research Needed, but not on Fire Science.
- Burning Money!
- Difficult to Collaborate.
- Working together?
- Collaboration, but how?

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