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Experimental Studies on Heat Release Rate in Chinese Kitchen Fires

H.H. Wu and W.K. Chow*
Research Centre for Fire Engineering
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hong Kong, China

*Corresponding author:

Tel: (852) 2766 5843; Fax: (852) 2765 7198

Email: beelize@polyu.edu.hk; bewkchow@polyu.edu.hk

Postal address: Department of Building Services Engineering, The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong.

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Abstract

Fire safety in kitchens of Chinese restaurants will be discussed in this paper. The licensing requirements and legislation aspects are outlined first with the past fire records briefly discussed. As identified, most kitchen fires in Chinese restaurants started from ‘cooking woks’ at the stoves. For assessing the thermal environment in a kitchen, heat release rates in burning such ‘woks’ in accidental fires should be measured. Two scenarios of burning woks with cooking oil were identified. The first scenario is a stove arrangement with only two woks. The second one is with six woks for serving banquet. Full-scale burning tests on those two identified scenarios were carried out at a remote area in Northeast China. The heat release rate was measured by the oxygen consumption method.

As sprinklers and water mist systems are commonly installed, the action of the sprinkler and water mist system on the cooking wok fires were also studied. The times of fire extinguishment upon discharging the water mist were also reported in evaluating the protection system. These experimental results would provide useful information for future designs of fire safety provisions in kitchens of large hotel groups in the Far East.

Keywords: heat release rate, accidental fire, fire safety, Chinese kitchens

1. Introduction

Consequent to many uncontrollable large fires in buildings, tunnels and subway stations, fire safety in public areas in the Far East is a concern. Hotel fire safety is now a hot issue due to the rapidly developing tourist industry in this part of the world with high density cities. Hotel fires happen everywhere including big cities like Hong Kong [1]. Most of them were controlled by the hotel staff, or with the sprinkler system operated. These fires occurred due to poor maintenance or low quality electrical installation and appliances in the guestrooms, kitchens and laundry areas.

Kitchens in hotels are considered areas with higher fire risk [2-4]. Gas stoves with high thermal power are installed in Chinese restaurants [5]. Some of them are illegal alterations of gas installations by increasing the gas flow rate without approval from the Authority. Such high thermal power is necessary to heat up the 'woks' (Chinese pans) quickly to prepare higher quality of food with 'wok-hay' (i.e. gases, steam and sometimes flame generated by dipping fresh food in hot oil with alcohol in the wok, a term to determine the quality of Chinese food). Such high power cooking woks might give rise to kitchen fires when the cooking oil inside is heated up above the auto-ignition temperature. New regulations are to be set up in some areas but this would take time for carrying out the associated research and development studies. It is a long procedure in going through the legislation bodies requiring several years.

Fire risk is usually specified in fire codes [e.g. 6] by the fire load density (FLD), the total amount of combustibles stored per unit floor area. The upper limit of FLD is 1135 MJm^{-2} in some cities

[6]. As the kitchen is small with high FLD, flashover would occur rapidly. Large amounts of heat and smoke would be produced and spread out to other areas. The space adjacent to the kitchen such as the dining hall would be affected as investigated before by zone models [5,6].

However, FLD itself is not sufficient to quantify fire risk. The fire scenarios in a kitchen have to be identified for hazard assessment. Heat release rate [7,8] is the first parameter to assess the consequences of the identified fire scenarios. It should be calculated accurately with updated theory and new instruments. There are not many such studies on heat release rate for kitchen fires in the literature. It is necessary to understand the probable heat release rates in an accidental fire of kitchen in a Chinese restaurant, before demonstrating the associated standards are applicable [9-11].

A series of full-scale burning tests were carried out to investigate the heat release rate of two different fire scenarios identified. Typical kitchens with woks and cooking oil commonly arranged in hotels were studied. The experiments were conducted in an experimental facility [5,12] at a remote town in Northeast China. Heat release rate was measured by oxygen consumption calorimetry [13,14].

Note that fire suppression systems are required in large commercial kitchens [2,6,9-11]. Sprinkler systems are commonly installed in such kitchens in many big cities [6]. Applying water spray to cooking pans and stoves might give adverse effects. New fire suppression systems such as water mist system [15-19] are acceptable. However, their performance in controlling fires from Chinese woks is not yet studied.

A sprinkler system and a low-pressure water mist fire suppression system were installed in the kitchen model. The cooking oil fires under the operation of sprinklers and water mist systems were studied. Effects of operating those water systems on the resulting heat release rates can then be evaluated.

2. Licensing Requirements

Fire safety in the kitchen of a restaurant has to be provided by following the local codes. Taking Hong Kong as an example, a restaurant should obtain a restaurant license before its operation as specified in Chapter 132 Public Health and Municipal Services Ordinance Part IV [20]. In order to obtain a license, the design should comply with hygiene requirements and the fire safety standards. Fire safety in two areas should be provided:

- Passive safety measures of the restaurant including the structural design, compartmentation, and means of escape [21-24].
- Active fire protection system [6,25] on at least four main areas: the fire service installations (in fact, these are active fire engineering systems), the usage of fuel, ventilation, and the means of access for fire fighters.

Fuel storage and the type of fuel used will be controlled to minimize the fire risk [26]. Normally, town gas, diesel oil and liquefied petroleum gas (LPG) are allowed. If diesel oil is used as fuel, it should be stored in a separate fire resistance chamber with an amount less than 500 litres [27].

In following local fire regulations [6,25] and subsequent hotel license requirements [28] for restaurants and kitchens, fire service installations are required. Sprinkler systems with fast response or higher temperature response heads are required. In addition, water mist and gas protection systems with clean agents such as heptafluoropropane are allowed. However, performance of the suppression system on kitchen fires is not yet evaluated. Such studies are necessary to support the specifications of fire safety provisions.

3. Kitchen Fires

From the statistical records on restaurant fires compiled by the local Fire Services Department [e.g. 1], most fires occurred in the kitchens. Very high thermal power stoves operated by either town gas or diesel oil were equipped for ensuring the quality of food. The major causes of fire were due to cooking appliances, electric faults and smoking materials. Over 50% of restaurant fires were originated from stoves as illustrated from the fire records. It is necessary to study cooking oil fires in Hong Kong [5].

About 50% of all accidental fires in hotels, restaurants and fast food outlets started in the kitchen involving cooking oil or fat fires [3]. As described [3], the fuel temperature can reach up to 400 °C for a cooking oil or fat fire and the auto-ignition temperature varies from 285 °C to 385 °C. The fuel temperature of conventional test fires for Class B such as a heptane fire is only 50 °C. Therefore, the cooking oil or fat fires are difficult to extinguish and easy to re-ignite, different from conventional liquid fuel fires. A new fire classification, Class F, is defined by some standard institutions such as the National Fire Protection Association, the British Standards Institution and the International Standards Organization [3,4]. It is different from the conventional class B liquid fires due to the high temperature involved.

Automatic sprinkler systems are generally installed and designed according to the common rules for automatic sprinkler installations as specified in the code [6]. Sprinkler systems should be designed to deal with Ordinary Hazard I as restaurants are classified under this hazard. The normal operating temperature for sprinklers in commercial buildings is 68°C. This type of

sprinkler is suitable for installation in the dining halls of restaurants. However, sprinkler heads with higher actuation temperature such as 79°C, or a longer response time index should be considered in kitchens. It happened before that sprinkler heads above the stove were actuated by the hot 'wok-hay'!

There is an increasing use of water mist system for kitchens [e.g. 15-19]. Water, carbon dioxide, halon gas (in the past) and powder types of extinguishers are commonly used.

4. Oxygen Consumption Calorimetry

Heat release rate can be measured [29] by the sensible enthalpy rise method, substitution method, compensation method and oxygen consumption method. Oxygen consumption method is now widely used [7] in bench-scale experiments such as the cone calorimeter, medium-scale rigs such as the furniture calorimeter and single burning items test, and full-scale burning tests such as the room calorimeter. All target to get some information on real fires. The concept was proposed by Thornton [13], and then developed later by Huggett [14] with rapid development of accurate gas sensors. The mass loss rate of oxygen for burning is measured first. The heat release rate can be estimated by multiplying it with the heat generated by burning a unit mass of oxygen for that fuel (similar to the calorific value for the heat generated per unit mass of fuel burnt). The heat generated per unit mass of oxygen consumed appears to be a constant for all normal fuel, about 13.1 MJ/kg oxygen consumed with $\pm 5\%$ accuracy.

An exhaust hood with a fan-duct should be constructed to collect the flue gas generated by the burning process. The heat release rate can be estimated by the oxygen consumption rate in the incoming air. The equations for calculating heat release rate by the oxygen consumption method were discussed by Parker [30,31] and Janssens [32] and Dlugogorski et al. [33]. For complete combustion, the equations concerned will be relatively simple. The heat release rate \dot{Q} (in kW) is given in terms of the mass flow rate of oxygen in the incoming air $\dot{m}_{O_2}^o$ (in kgs^{-1}), the mass flow rate of oxygen in the exhaust gas \dot{m}_{O_2} (in kgs^{-1}) and the universal constant E as follows,

$$\dot{Q} = E(\dot{m}_{O_2}^o - \dot{m}_{O_2}) \quad (1)$$

However, incomplete combustion is likely in the fire tests. Concentrations of other species such as carbon dioxide and carbon monoxide have to be measured for accurate calculations. For convenience, condition of incoming air for burning is assumed to be the same as ambient air. Concentrations of oxygen, nitrogen, carbon dioxide and water vapour are constant. Carbon monoxide in the incoming air $X_{CO}^{A^o}$ is not included. Carbon dioxide concentration in the air $X_{CO_2}^o$ is approximately 330 ppm. Water vapour in the air $X_{H_2O}^o$ is calculated in terms of the relative humidity, ambient temperature, ambient pressure and saturation pressure of water vapour at that temperature.

When only oxygen is measured, both water vapour and carbon dioxide should be removed before measuring oxygen. The mole fraction of carbon monoxide is taken as zero. The equation of heat release rate \dot{Q} is given by:

$$\dot{Q} = E \frac{\varphi \cdot \dot{m}_e}{1 + \varphi(\alpha - 1)} \frac{M_{O_2}}{M_a} (1 - X_{H_2O}^o - X_{CO_2}^o) X_{O_2}^{A^o} \quad (2)$$

The oxygen depletion factor is given by:

$$\varphi = \frac{X_{O_2}^{A^o} - X_{O_2}^A}{(1 - X_{O_2}^A) X_{O_2}^{A^o}} \quad (3)$$

The expansion factor α is measured to be 1.105 for common burning fuel.

Equation (2) based on only measuring oxygen is the most commonly used equation. It is easier to carry out the test with only an oxygen analyzer. However, high values of error are expected for burning with high concentration of carbon monoxide and soot released.

The oxygen consumption method might require some modifications on heat release rate measurements for specific circumstances as in fire suppression experiments. Part of the heat is taken away due to vaporisation of water mist. This should be taken into account [33] by including percentage of water. However, water content was not measured in the tests due to resources limitation. This would be key issue to get valid measurement in future studies.

5. The Kitchen Model

To assess how sprinkler and water mist would control a fire, full-scale burning tests were carried out. Kitchen fire scenarios with and without the operation of sprinklers and water mist systems were considered. A full-scale burning facility for measuring heat release rate in different building arrangement was developed [12] in a remote town Lanxi, about 150 km from Harbin, Heilongjiang, China. A model Chinese kitchen with an exhaust hood and a fan-duct system as in Fig. 1 was constructed with flashover kitchen fires studied.

Cooking oil in the woks over the stove was burnt. Heat release rates were measured by the oxygen consumption method [7,13,14]. Results on the heat release rate are useful for fire hazard assessment on kitchen fires on agreeing an ‘initial design fire’ at the starting-up stage. The experiments do not involve other fuel that may be ignited and contribute to the fire. As noted by the authors, kitchens have high fuel load density. A starting fire can quickly spread to involve items other than the ignition source. Results on heat release rate from this study are useful for studying consequences of different scenarios with fire models. The two identified scenarios were typical setups in Chinese restaurants in hotels:

- Burning cooking oil in two woks in a gas stove for a staff canteen. Two woks will be used in serving meals for staff canteen under normal operation. The cooling oil in the woks was burnt.
- Burning cooling oil in six woks in a large banquet. In serving banquet in a hotel, six woks will be used to prepare food quickly for 1200 persons, usually 100 tables with 12 persons per table.

6. Full-Scale Burning Tests

Two groups of six kitchen fire tests were carried out as follows:

- (i) Group A arrangement on a kitchen for a Chinese restaurant functioning as a hotel staff canteen with two woks:

Such an arrangement is shown in Fig. 1a. Each wok was filled with 1000 ml soyabean oil.

Three scenarios were considered:

- Test A1: Fire only.
- Test A2: Fire with the operation of water sprinkler system.
- Test A3: Fire with the operation of water mist system.

- (ii) Group B arrangement on a typical larger kitchen of a Chinese restaurant for banquet with six woks:

Each wok was filled with 1000 ml of soyabean oil as in Fig. 1c. Three scenarios were identified:

- Test B1: All six woks on fire.
- Test B2: All six woks on fire with the operation of water sprinkler system.
- Test B3: All six woks on fire with the operation of water mist system.

The kitchen model is of length 3.6 m, width 2.4 m and depth 2.4 m as shown in Fig. 2a. Flue

gas liberated would be extracted by a fan-duct system through the exhaust hood at a door opening of width 0.8 m and length 2 m. A stainless steel table long enough to set up six woks and two sinks was constructed as in Fig. 2b. The woks filled with oil were ignited as shown in the photographs. Tests were then repeated by operating the sprinkler system and the water mist fire suppression system. The operating pressures were 1.12 MPa and 1.26 MPa; and flow rates 5 l/s and 0.2 l/s respectively for the two systems. Note that the flow rate of the water mist system was only 4% of that for sprinkler.

Ambient air temperatures were from 18 °C to 22 °C, relative humidities from 50% to 90% while carrying out the experiments from July to September in 2005. Results on oxygen consumption and heat release rate are shown in Figs. 3 and 4.

7. Results on Group A Tests

Two woks filled with soyabean oil as in Fig. 2c were tested.

- Test A1

Smoke was generated when the oil was heated. After about 7 min after ignition, the oil was ignited. A sharp increase in heat release rate is shown in Fig. 3.

- Test A2

After the gas stoves were lit, it took 4 min 55 s and 7 min 54 s respectively for the cooking oil to be lit at pan A and B. The sprinkler system was turned on after 9 min 50 s. No splashing or spillage of oil was observed. The fire was extinguished after 10 min 1 s. The total extinguishing time is 601 s. The heat release rate is also shown in Fig. 3.

- Test A3

After the gas stoves were lit, it took about 6 min 13 s for the oil to be ignited. The gas valve was then shut. After another 2.5 min, the water mist system was activated. It took 16 min 7 s for the water mist system to extinguish the fire. The total burning time is 25 min 20 s but burning with a very small flame at the later stage. Therefore, only part of the heat release rate curve is shown in Fig. 3 for comparing with other tests.

8. Results on Group B Tests

All six woks as in Fig. 2d were burnt.

- Test B1

It took 6 min 20 s for fire to be ignited at wok A1, 6 min 35 s at wok A2, 4 min 45 s at wok A3, 5 min 34 s at wok B1, 5 min 10 s at wok B2 and 6 min 10 s at wok B3.

The fire was extinguished after 9 min 14 s at wok A1, 15 min 59 s at wok A2, 13 min 30 s at wok A3, 8 min 50 s at wok B1, 8 min at wok B2 and 16 min 10 s at wok B3.

The heat release rate is shown in Fig. 4.

- Test B2

It took 5 min 32 s for fire to be ignited at wok A1, 6 min 20 s at wok A2, 7 min 16 s at wok A3, 6 min 27 s at wok B1, 6 min 11 s at wok B2 and 6 min 37 s at wok B3.

The water sprinkler system was activated 8 min 7 s after the gas stove was lit. No splashing or spillage of oil was observed in test A2. Water discharge was stopped at 8 min 20 s. The oil was re-ignited and water was turned on again at 8 min 57 s. The cooking oil fire was completely extinguished at 10 min 50 s. The heat release rate is shown in Fig. 4.

- Test B3

It took 6 min 14 s for the fire to be ignited at wok A1, 7 min 5 s at wok A2, 7 min 9 s at wok A3, 6 min 27 s at wok B1, 6 min 35 s at wok B2 and 6 min 40 s at wok B3.

The water mist system was activated at 9 min 33 s after the gas stove was lighted. It took 19 min 3 s to extinguish the oil fire. The heat release rate is shown in Fig. 4.

9. Discussion

Six tests were conducted in a sample kitchen with two or six woks burning.

On group A arrangement with two woks burning, the environment was quite smoky in test A1. The maximum heat release rate went up to 0.4 MW. In test A2, the sprinkler system needed less time, within a total duration of 20 min, to extinguish the fire completely for the same setup. In test A3, the water mist system was effective in extinguishing the fire in about 25 min. Time for extinguishing the fire was only 4% of the extinguishing time recorded for sprinklers.

On group B arrangement with six woks burning, the maximum heat release rate was up to 1.4 MW for test B1. On this particular test, flame moved out of the door, satisfying one of the criteria for onsetting flashover. Equations derived on estimating maximum heat release rate \dot{Q}_{mf} in flashover were reviewed and compared [34]. The equation by Thomas et al. [35] on \dot{Q}_{mf} agrees well with experiment in this room calorimeter. It is related to ventilation factor $A_v \sqrt{H_v}$, where A_v and H_v are vent opening and height respectively as:

$$\dot{Q}_{mf} = 378A_v \sqrt{H_v} + 7.8A_T \quad (4)$$

A_T is the total area of room which depends on room length L of 3.6 m, room width W of 2.4 m and room height H of 2.4 m minus the ventilation opening area A_v given by:

$$A_T = 2(L+W)H + 2LW - A_v \quad (5)$$

A_T is 44.48 m² and therefore \dot{Q}_{mf} is 1.2 MW given by equation (5). The measured 1.4 MW is over that and so flashover should be onsetted with flame moving out.

In test B2, the sprinkler system took less time in comparing with test B3 with water mist system to extinguish the fire. It appears that water mist under the design condition is not as effective in suppressing bigger wok fires.

The operation effect of sprinkler systems and water mist systems on burning cooking oil in woks on stove were studied. This would give some indication on how the fire suppression system would perform on the starting up fire. Both water systems are effective in extinguishing the fire rapidly. From the above preliminary tests, it appears that the sprinkler system is efficient in extinguishing the fire. No splashing or spillage of fuel was observed for the wok arrangements in the kitchen model. However, more water is required in operating the sprinkler system. For a 3 m cubic room rated as ordinary hazard class, the water flow rate for a sprinkler head is 45 litres per minute to give a water discharge density of 5 mm per minute in the protected area. The flow rate for a water mist nozzle in a low pressure suppression system is down to 5.4 litres per minute as the required water density is only 0.2 litres per minute per m³ of space volume.

The times taken by the sprinkler and water mist systems measured in above are not taken as an extinguish time in a real kitchen fire as other fuels and combustibles are not involved. It is interesting to observe that the water mist system controlled the fire at about the same heat release rate as the sprinkler system in the case of the six wok fire. In the case of the two wok fire, the heat release rate under action of water mist was even significantly higher than on operating the

sprinkler system. Higher heat release rate in using water mist system was measured due to initial expansion of flame volume upon operating the system. Such extinguishing mechanisms on starting up fire would be studied in the future by including chemical suppressing reactions of water mist on the particular fuel type.

10. Conclusions

Fire safety in hotel kitchens in Hong Kong [5] was discussed with the code and licensing requirements reviewed. Heat release rates in burning woks in Chinese restaurants were studied by six full-scale burning tests on two identified scenarios.

Two different wok arrangements in a kitchen model in Chinese restaurant were set up in a remote area of Northeast China. The heat release rate was measured by the oxygen consumption calorimetry.

As observed, a wok fire might be developed to onset flashover in the kitchen. The heat release rate would increase to give bigger fires. Fire suppression systems must be installed.

Both sprinkler and water mist systems are demonstrated to be effective in extinguishing the fire under the tested scenarios. However, different kitchen geometries with different wok arrangements would give different fire environments. Procedures in designing fire suppression systems for local kitchens in this part of the world should be modified [9-11] from overseas studies. Similar tests are recommended to confirm the performance of the systems. This is particularly important for open kitchens in small residential units of very tall buildings [36]. Obviously, cooking with woks is not allowed in those open kitchens.

11. Additional Comments

The paper was published as a journal paper [37]. With the practice of publisher, preprint is allowed to upload at a website. There are further studies on this topic [38-56].

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JAFS-HRRKitchenFire2

A445UL22-1c

Record:

A445UL22-1a (opened 14 June 2023, open from JAFS-JRRKitchenFire2.doc)

A445UL22-1b (opened 26 June 2023)

A445UL22-1c (opened 27 June 2023)

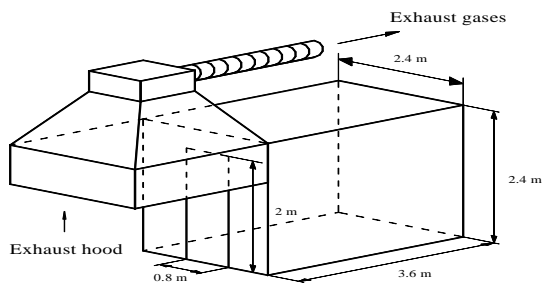


(a) Staff canteen kitchen

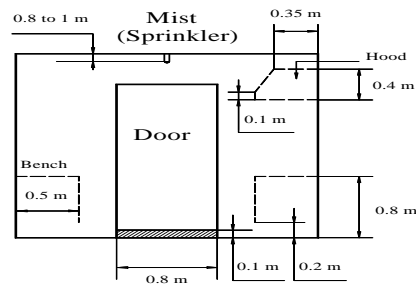


(b) Banquet kitchen with 6 woks

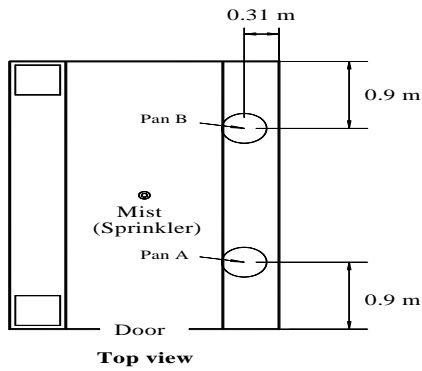
Fig. 1: Hotel Chinese restaurant kitchens tested



(a) The room



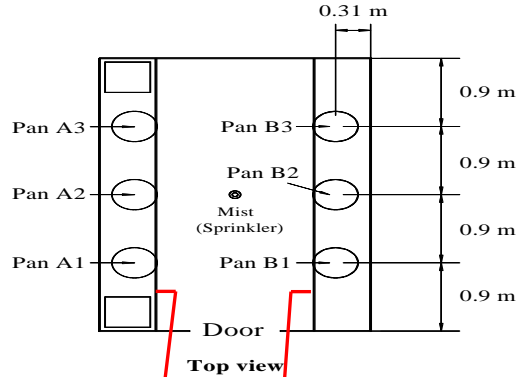
(b) Front view



Top view



(c) Scenario A



Top view



(d) Scenario B

Fig. 2: The kitchen model

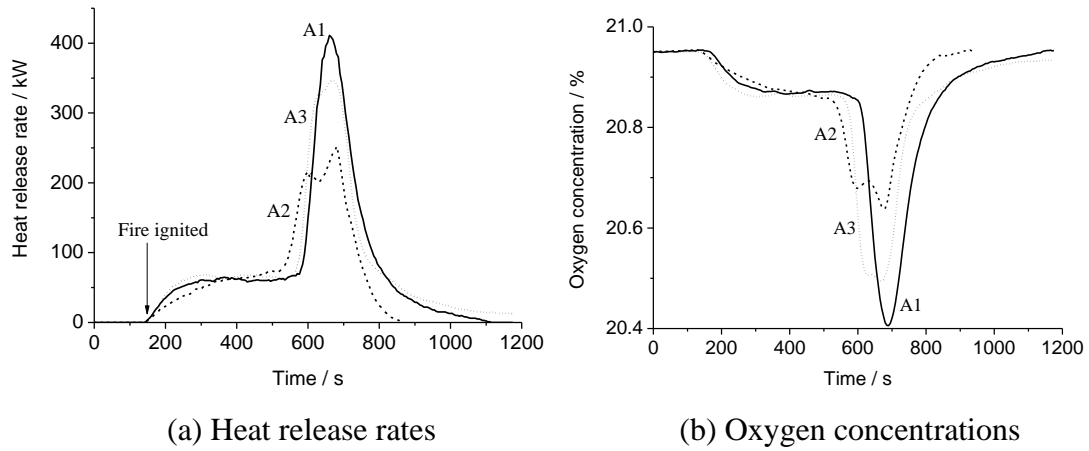


Fig. 3: Results for group A tests

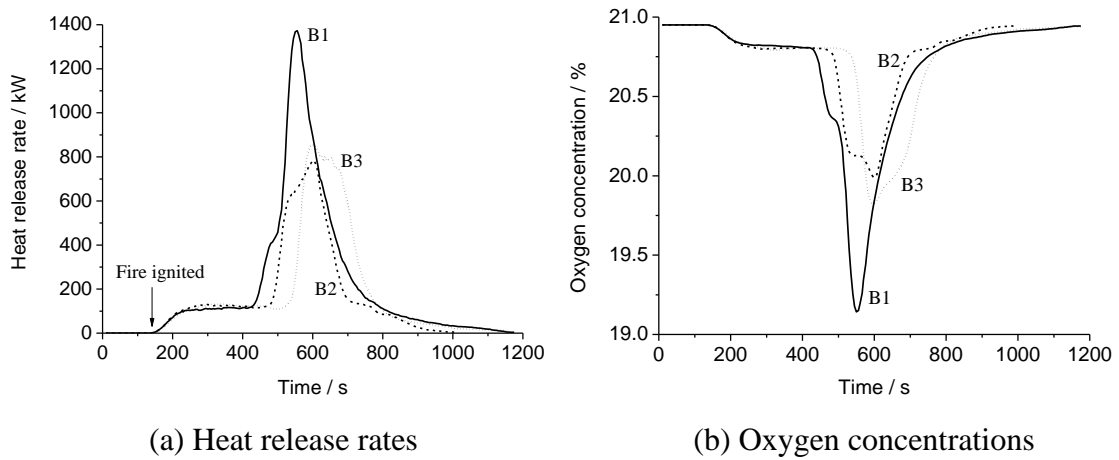


Fig. 4: Results for group B tests