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# Time-dependent smoke yield and mass loss of pool fires in a reduced-scale mechanically ventilated compartment

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## ABSTRACT

Technical and pure grades of the combustibles heptane and dodecane were used in a series of small-scale fire tests conducted in a 1 m<sup>3</sup> compartment that was mechanically ventilated at 5 and 8 air changes per hour (ACH). Combustible mass loss rates, soot mass concentrations, soot size distributions, several gas species concentrations, and compartment temperatures were measured during the fire. Results for the two pure-grade hydrocarbons were compared with results obtained for their respective technical grades. Technical-grade dodecane produced the highest soot emissions; pure n-heptane produced the lowest. Soot size distributions of all four combustibles attained a steady profile whose modal diameter was about 200 nm. Underventilated fires showed higher carbon monoxide yields than soot yields. Both compartment ventilation rates produced similar results, although the fire self-extinguished earlier for 5 ACH.

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## 1. Introduction

Compartment fires are controlled primarily through ventilation, heat loss, and the size of the fire source. The growth kinetic or the maximum heat release of such fires must be known to determine their risk and damage potential. Mechanically ventilated compartments are often used at industrial facilities, especially for dangerous substances such as radioactive materials. Accidental fires occurring in these facilities can be a serious issue because the dangerous substances risk polluting the environment. It is therefore critically important to gain a better understanding of these fires and of their characteristics, such as heat release rates, combustible mass loss rates, and the production of carbon monoxide and soot.

Numerous studies have collected carbon monoxide and soot production data for underventilated fires in reduced-scale compartments [1–13]. Beyler used a hood, and most of the other studies were performed with gas combustibles (using a burner) or with a naturally ventilated compartment [4–9]. Mulholland et al. used a controlled atmosphere cone calorimeter to determine carbon monoxide and soot yields for various gas and solid combustibles (methane, propane, ABS, PMMA, and wood). Similar to the present study, Aljumaiah et al. measured carbon monoxide and soot yields for liquid combustibles in a 1.6 m<sup>3</sup> mechanically ventilated compartment. Lassus et al. [11–12] determined absolute

values for carbon monoxide and unburned combustible vapors in relation to oxygen levels in a larger 8 m<sup>3</sup> compartment. However, none of these previous studies has examined time-dependent mass and number concentrations of soot particles during the growth of the fire. This is an important consideration because different ventilation conditions are encountered during the growth of the fire and may induce variations of the smoke production may produce variations in the fire's behavior during its development.

The present study measured gas species, soot concentrations, and mass loss rates of underventilated pool fires in a 1 m<sup>3</sup> mechanically ventilated compartment. Tests were performed at 5 and 8 air changes per hour (ACH) and under free-burning conditions. The selected ACH values are representative of those encountered in industry, in particular in nuclear installations.

Four combustibles were used: pure n-heptane, technical-grade heptane, pure n-dodecane, and technical-grade dodecane. The technical grade of a hydrocarbon is of a lower quality compared with its pure form. Heptane is a liquid hydrocarbon commonly used in fire studies. Dodecane, a hydrocarbon similar to tributyl phosphate (TBP) and hydrogenated tetrapropylene (HTP) mixtures, is a chemical solvent used in nuclear combustible processing plants. The two hydrocarbons differ in flammability. The study compared mass loss rates and smoke characteristics for the pure and technical grades of both hydrocarbons.

Sections 2 and 3 describe the experimental setup and the fuel properties. Section 4 presents the experimental measurements,

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followed by a discussion of the results and a comparison of smoke and mass loss rates with data found in the literature.

## 2. Experimental setup

The fire experiments were conducted in a mechanically ventilated 1 m<sup>3</sup> airtight steel compartment (Fig. 1). The inner walls, ceiling, and floor of this compartment were covered with a 25 mm thick ceramic fiber blanket for thermal insulation. Attached to hinges, one wall remained adjustable and could function as a door. At the bottom of this door, a ceramic glass window (30 cm × 30 cm) allowed the visual observation of the fire during tests. The air-inlet was situated on a sidewall near the floor. A vertical plate was placed in front of the inlet to break the current of the incoming air. Smoke was evacuated with an electric fan through a ceiling exit located near the sidewall opposite the air-inlet.

Two kinds of fire test—open and closed—were performed in this compartment. For open burning tests (called “free-burning”), the door remained completely open, and the smoke extraction fan operated at maximum capacity. Gas concentration measurements around the fuel pan during these open burning tests indicated that ambient conditions existed for the surrounding air that fed the flame. For closed burning tests, the door was shut using latches, and the fan’s operating power was adjusted to the desired airflow rate, thereby creating underventilated burning conditions.

A vertical array of 8 thermocouples (K type, 0.5 mm) was placed at various heights below the smoke exit to measure the temperature of the atmosphere inside the compartment. The first thermocouple was located at a distance of 10 cm from the floor, and the remaining ones were regularly spaced 10 cm. Placed under the fire compartment, a Mettler Toledo weighing scale (0.1 g resolution) took continuous measurements of the fuel mass. A cylindrical shaft with a water seal connected the scale to the fuel pan inside the compartment. (Utiskul et al. used a similar airtight weighing system). A Testo 350 gas analyzer measured oxygen, carbon dioxide and carbon monoxide gas concentrations in the smoke evacuation duct. Oxygen and carbon monoxide concentrations of the gases near the fuel pan were also measured at floor level around the fuel pan with an ECOM J2KI gas analyzer. This gas analyzer was equipped with a Y-shaped probe to extract

the gases around the fuel pan. The air changes per hour (ACH) of the compartment were determined with a diaphragm. A Furness Controls differential pressure sensor with a 0.1 Pa resolution measured pressure differences between the upstream and the downstream of the diaphragm orifice, which allowed the calculation of the airflow rate. For each test, a video of the flame was recorded with a camera positioned in front of the compartment window.

The following aerosol metrology equipment was used to determine certain physical characteristics of the soot particles produced in each test: A DEKATI fine particulate sampler (FPS) sampled the smoke below the exit and then diluted it. This FPS device is well suited for aerosol measurements under hot and humid conditions. The samples were then channeled to two other devices: a TEOM (tapered element oscillating microbalance R&P 1105) and a DMS 500 (differential mobility spectrometer). The TEOM took real-time measurements of the mass concentration of soot particles. It is an apparatus based on the principle of an inertial microbalance [14], and it is in accordance with the traditional filter method used to determine total mass concentrations [15]. The system’s minimum detectable mass is given as 10 ng (manufacturer’s datasheet), providing a measurement accuracy of 2 mg/m<sup>3</sup> for the soot mass concentration established during 1 s. The DMS 500 is a commercial particle size analyzer that uses electrical mobility measurements to determine the electrical mobility diameters of soot particles in real time. Measurements taken by these two devices were corrected later, taking into account the dilution ratio of the FPS.

This system presents the advantage of continuously taking real-time measurements to determine soot characteristics instead of using glass microfiber filters to trap soot particles [2,13], in which case only a limited number of measurements can be obtained for each test.

Data measured by all instruments were recorded at a rate of at least 1 Hz during tests. For each combustible, tests were performed at 5 and 8 ACH and under free-burning conditions.

For all tests, the liquid combustibles were held in a borosilicate glass fuel pan with a rim height of 8 cm and a diameter of 19 cm. Ceramic fiber insulation was placed below the fuel pan to prevent heat transfer to the weighing scale.

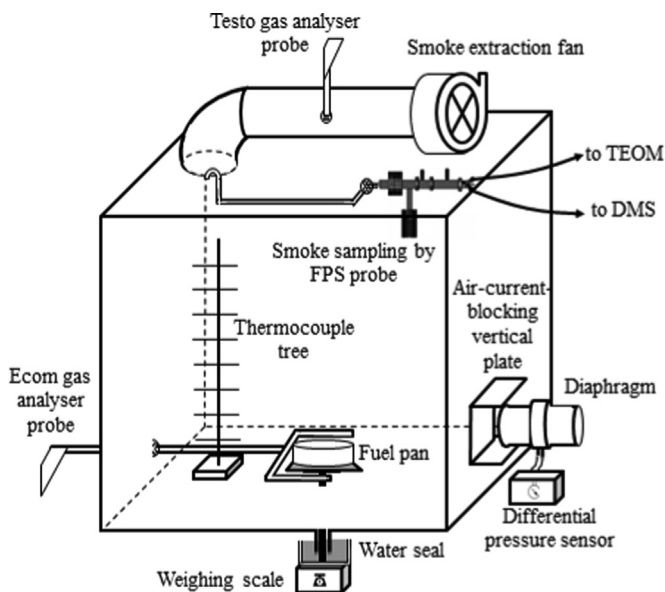


Fig. 1. Experimental setup.

## 3. Fuel properties

The following section examines what are considered the most important fuel properties for fire studies according to Quintiere [16]: heat of combustion, heat of vaporization, and boiling temperature. In terms of chemical composition, measurements taken with a Bruker SCION 456 chromatograph showed that the technical-grade hydrocarbons were composed mostly of other isomers of the same hydrocarbon molecule. Table 1 provides a summary of the chromatography results. An isoperibol bomb calorimeter (Parr Instrument Company, model 1356) was used to determine the heat of combustion, assuming a vapor state for the water component of the combustion product. These calorimetric tests showed that the values for technical-grade hydrocarbons were almost identical to the values of their pure counterparts (Table 1). There was a mere 1% difference between technical-grade products and pure products. Heptane and dodecane had very similar heat of vaporization values (at 25 °C) (Table 1). However, they exhibited significantly different boiling temperatures: 371 K for pure heptane and 489 K for pure dodecane. In addition, smoke point heights can be used to rank the tendency of a combustible to produce soot.

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