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Design fires with mixed-material burning cribs to determine the extinguishing effects of compressed air foams

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ABSTRACT

This study evaluates the efficacy of compressed air foam (CAF) in comparison to common fire extinguishing media. Newly developed mixed-material burning cribs were used as a normative fire load for extinguishing tests to accurately represent the significantly elevated utilization of synthetic materials in everyday life. A series of outdoor experiments was carried out to analyze the effectiveness of the fire extinguishing medium CAF using synthetical class-A foaming agents from two different manufacturers, and compared them to water and water-foam solution as a function of the extinguishing distance. In a second series, performed inside a fire room, the efficiency of CAF-usage in indoor fires was evaluated. Moreover, the results of the indoor test series provided information about the composition of smoke gases based on the kind of extinguishing tactic used to suppress the fire. The results showed that under the tested conditions CAF suppressed fire more effectively than both water and water with foaming agents. CAF was able to wet areas hardly accessible to other extinguishing media, and due to its various simultaneously occurring effects and its compact jet with high kinetic energy, it cooled down temperatures more efficiently than water or water-foam solution.

1. Introduction

Due to the rapid progress of technical and chemical development during the last century, new possibilities for production engineering and configuring the ordinary life settings are accompanied by unprecedented dangers. One of the finest examples of this change is the overwhelming amounts of different synthetic materials used in everyday life [1]. Various additives contained in synthetic materials exhibit completely different fire behavior, with more intensive characteristics than an ordinary wood fire [2,3].

Accidental fires in tire storages, landfills, or factories have a disastrous impact on the environment and provide media attention. Such fires are difficult to extinguish once ignited. Often, numerous firefighters need to combat the fires for several days or even weeks. This means not only an enormous technical and human effort but also a high risk for firefighters [4], population and environment [5]. Therefore, it is necessary to provide a well-researched and effective extinguishing agent to suppress hostile fires as quick as possible and to minimize the hazards.

Previous research [6,7] indicated that compressed air foams (CAF) have the capability to combat such fires effectively. The first investigations of CAF were performed in the 1940s [8]. Fifty years later, the first professional fire brigades installed firefighting systems based on this substance in their fire trucks. Field reports show that CAF has often been used effectively for firefighting and achieved good extinguishing results. Pure water is not able to attain similar results in comparable fire scenarios [8,9]. Nevertheless, systematic scientific research on the extinguishing effects of CAF is required before nationwide application of CAF in mobile firefighting.

This paper discusses a series of design fires. Ten outdoor and four indoor tests were performed to prove the effectiveness of CAF in class-A fires with a high content of synthetic materials. When examining an extinguishing agent, which needs to be highly effective in suppressing fires of different synthetics, it is important to use a complex but easily reproducible fire load with a behavior close to reality. Depending on their operation area, ordinary wood crib constructions have been used for fire tests for decades [10] and are standardized in several different guidelines, such as [11] and [12]. With the aim of developing a design fire simulating facilities with a high content of synthetic materials, we constructed a multicomponent crib based on these guidelines. By adding different synthetic fire loads to a wooden framework, the fire behavior was adjusted to place high demands on the extinguishing agents' efficacy.

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Nomenclature listing

H_i	calorific value of any material (kWh/kg)
$\overline{H_c}$	average calorific value of a crib (kWh/kg)
$\overline{H_{lr}}$	average calorific value of a living room (kWh/kg)
m_i	mass of any material (kg)
m_c	mass of a crib (kg)
q	heat flux (kW/m^2)
Q_{max}	maximum heat release rate (kW)
s	extinguishing distance (m)
t	time (sec)
W	effective heat capacity (kWh)
Greek	
$\overline{\vartheta_c}$	average crib temperature (°C)
$\Delta\overline{\vartheta_c}$	deviation of average crib temperature (°C)

2. Developing a new mixed-material burning crib

The construction of the mixed-material burning cribs bases on a qualitative and quantitative inventory of all furniture and fixtures as well as their weights in five different living rooms [13]. Data extracted from this inventory are shown in Table 1. The average calorific value $\overline{H_{lr}} = 5.589$ kWh/kg of all of the materials contained in a living room is calculated from equation (1). This value was translated into a design fire presenting a maximum heat release rate of $Q_{max} = 1,000\ldots 2,500$ kW over a period of 800 s. The heat capacity provided by these conditions is calculated in equation (2). Equation (3) calculates the calorific value as a function of a crib's mass, needed to obtain the specified values.

$$\begin{aligned}\overline{H_{lr}} &= \sum m_i \cdot H_i \\ \overline{H_{lr}} &= 5.5891\ kWh/kg\end{aligned} \quad (1)$$

$$\begin{aligned}W &= Q_{max} \cdot t \\ W &= 2,500\ kW \cdot 0.22\ h \\ W &= 555.5556\ kWh\end{aligned} \quad (2)$$

Table 1
Materials mass fraction in a common living room and material values of the novel mixed-material burning crib.

Material	Mass fraction $\mathbf{m_i}$ in a common living room [%]	Material calorific value $\mathbf{H_i}$ [kWh/kg]	Set value in the mixed-material burning crib [kg]	Material density [g/cm³]
Wood compound/ wood/paper	70.00	4.40	69.58	0.55–0.59
Polyvinyl chloride (PVC)	2.90	5.00	2.88	1.44
Polyurethane (PU)	4.50	6.70	4.47	1.31
Polypropylene (PP)	2.90	12.20	2.88	0.91
Polyamide 6 (PA6)	0.90	7.90	0.89	1.17
Polyethylene (PE)	2.30	12.20	2.29	0.92
Polycarbonate (PC)	5.50	8.30	5.47	1.16
Polyethylene terephthalate (PET)	5.40	6.10	5.37	1.36
Acrylonitrile-butadiene-styrene (ABS)	4.20	9.90	4.17	1.04
Polystyrene (PS)	1.40	11.10	1.39	1.05
	$\Sigma =$ 100.00	$\overline{H_{lr}} =$ 5.5891	$m_K =$ 99.40	

$$\begin{aligned}m_c &= W / \overline{H_{lr}} \\ m_c &= 555.5556\ kWh / 5.5891\ kWh \cdot kg^{-1} \\ m_c &\approx 99.40\ kg\end{aligned} \quad (3)$$

The allocation of materials inside the novel mixed-material burning crib, resulting from earlier calculations, is shown in Table 1.

The skeletal structure of the mixed-material burning cribs consists of twelve stacked layers of eight parallel pine sticks, with a front side of 40 mm × 40 mm square. Each pine stick in every layer has a length of 880 mm and is oriented perpendicular to the sticks of the adjacent layer. Adjacent sticks are separated by gaps of 80 mm. The resulting crib is a square base 880 mm × 880 mm in area and 480 mm high. To prevent the pine sticks from shifting during extinguishment, they are fixed with 6 mm beech wood plugs. The wood's residual moisture content was 12 ± 2% at the time of delivery. At the time of the fire tests, after four-week storage in a climatic chamber, the wood's residual moisture content was 5 ± 1%. The fluctuating resin content in each pine stick entails variation in the weights of the crib's skeletal structure between 74.5 and 79.0 kg. The wood allotted for the cribs for the indoor fire tests came from a different delivery, also with a residual moisture content of 12 ± 2%. After air-conditioned storage for one week before the indoor fire tests, the residual moisture content was 11 ± 2%. In this case, the skeletal structures of the crib weighed between 78.4 kg and 81.3 kg.

The synthetic materials are inserted horizontally into the side of the crib. The synthetic materials have the form of boards with a length of 500 mm, a width of 47 mm and a material thickness of 4–8 mm, depending on production. In order to avoid interrupting the stacking effect, the synthetic material boards are positioned diagonally and upright on their longitudinal side, in the spaces between the sticks. Depending on their thickness, the boards are inserted separately or by bundles. As the boards lean against the stick adjacent on the right, the sticks were spaced by at least 40 mm to ensure that the path of hot gases could spread vertically. To prevent overlapping synthetic material boards, and with it blocked flow channels to the center of the crib, the boards are inserted up to a length of no more than 440 mm. The remaining 60 mm hang over the crib sides and offer a larger contact surface for the flames. The boards are fixed with 6 mm beech wood plugs as well. The allocation of the boards throughout the crib is determined by their burning characteristics. Flame resistant materials and materials that cannot sustain burning independently, such as polycarbonate and polyethylene terephthalate, are positioned in the lower part of the crib, because of the high thermal stress provided by the source of ignition. Normally inflammable synthetic materials are arranged in the upper part of the crib so that they will be conserved until the fire is fully developed. Fig. 1 shows the construction drawing of the crib and the exact allocation of all the synthetic material boards.

3. Outdoor fire tests

3.1. Experimental set-up

The mixed-material burning crib design fires with a normative fire load were intended to provide reliable results about the effectiveness of CAF after multiple repeated tests at the fire test ground of the Federal Institute for Material Research and Testing. For data acquisition, the experimental setup featured a comprehensive range of analytical measurements. The experimental setup is shown in Fig. 2.

The mixed-material burning crib (a) stood on a grid 0.2 m above a tray of 1.0 m × 0.9 m with a 0.05 m high wall containing inflammable matter. A tripod 2.0 m high (b) was positioned over the crib. Most of the thermocouples and the sensor of the Fourier Transform Infrared- (FTIR) spectrometer, positioned centrally above the crib at a height of 1.5 m, were fixed to the tripod. The sampling gas was conveyed to the FTIR spectrometer (Gasmet Dx4000N, Ansyco GmbH) through a 2μm glass fibre particle filter, located directly behind the probe tube and a 0,1μm glass fibre particle filter located at the pump inlet. The gases were