

Influence of modern plastic furniture on the fire development in fires in homes: large-scale fire tests in living rooms

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Funding information

Bundesministerium für Bildung und Forschung, Grant/Award Number: 13N12176

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SUMMARY

About 80% of all fire fatalities in Germany occur because of fires in homes. It has been known for some time that modern materials (synonym for materials consisting mostly of synthetic polymers) tend to burn differently from older materials (synonym for materials consisting mostly of fibrous cellulosic substances) and it has been acknowledged that the amount of combustible plastics in homes has increased significantly over the last decades. To investigate the influence of modern furniture and ventilation conditions of fires in homes, a series of four large-scale tests in two living rooms (LRs) with adjacent rooms (ARs) was performed by BAM and the Frankfurt fire service. Two LRs, one with older furniture and one with modern furniture, were tested twice each. Each test started with the ignition of a paper cushion on an upholstered chair. The influence of modern materials on the fire development was investigated, as well as the influence of the ventilation on the fire development. In all settings, an upholstered chair was the first burning item. Results of the test series show that fires in rooms with modern furniture develop faster than fires in rooms with older furniture. This is true for temperature development in the rooms as well as for smoke production.

KEYWORDS

room fire, furniture, modern, gas analysis, smoke

1 | INTRODUCTION

Fires in homes cause about 80% of all fire fatalities in Germany.¹ U.K. statistics, which are much more detailed than German statistics, show that living and bedroom fires are more often responsible for fatalities than kitchen fires. In the United Kingdom, kitchen fires occur much more often.² According to the U.S. fire statistics, in the years from 2010 to 2014 alone, there were 5630 home fires that can be traced back to the ignition of upholstered furniture. These fires caused 440 deaths and more than 260 million U.S. dollar in property damage. From this fire statistics, it can also be deduced that an average of 1 in 13 reported upholstered furniture fires resulted in

the death of people.³ It has been known for some time that modern materials tend to burn differently from older materials, and it has been acknowledged that the amount of combustible plastics in homes has increased significantly over the last decades.⁴⁻⁸ In this paper, the terms “old” in comparison to “modern” furniture were used. In the early 1940s, furnishings consisted mainly of cellulose-containing materials such as wool and cotton. However, the increasing use of materials based on wood and polymers is leading to a change in the material composition of furnishings in homes. The furnishings used for the investigation of this paper were briefly defined as “old,” because they tend to contain cellulose-containing materials, and “modern” tend to consist of different synthetic polymers. The

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aim of this investigation was to describe the influence of these changed material composition of furnishings on the course of room fires as well as on the associated energy and mass release. In addition, the influence of ventilation conditions was examined. Therefore, a test series of four experiments in living rooms (LRs) with adjacent rooms (ARs) has been performed with the Frankfurt fire service and BAM, the German Federal Institute for Material Research and Testing. The four tests aimed on investigating on one hand the influence of older and modern furniture and ventilation conditions on the fire and smoke development of fires in homes, and on the other hand to assess the differences in conditions for inhabitants, who are in the room of fire origin or in the AR.⁹ In all four large-scale experiments, a

similar furnishing of the LR has been used, which is seen to be typical for German LRs approximately 30–40 years ago and today. The modern furniture had been purchased new in a very popular Scandinavian furniture store, the old furniture had been purchased second-hand. The old furniture is used in contrast to the modern furniture.

In two experiments the old furniture was used, and in two experiments modern furniture was used. The experiments had different ventilation conditions, which were realised by open and closed windows, see next section for details. With temperature measurements in the room of fire origin and the AR and gas measurements in the AR and video footage inside the rooms, the fire and smoke development could be assessed. In all four experiments, an upholstered chair was chosen as the

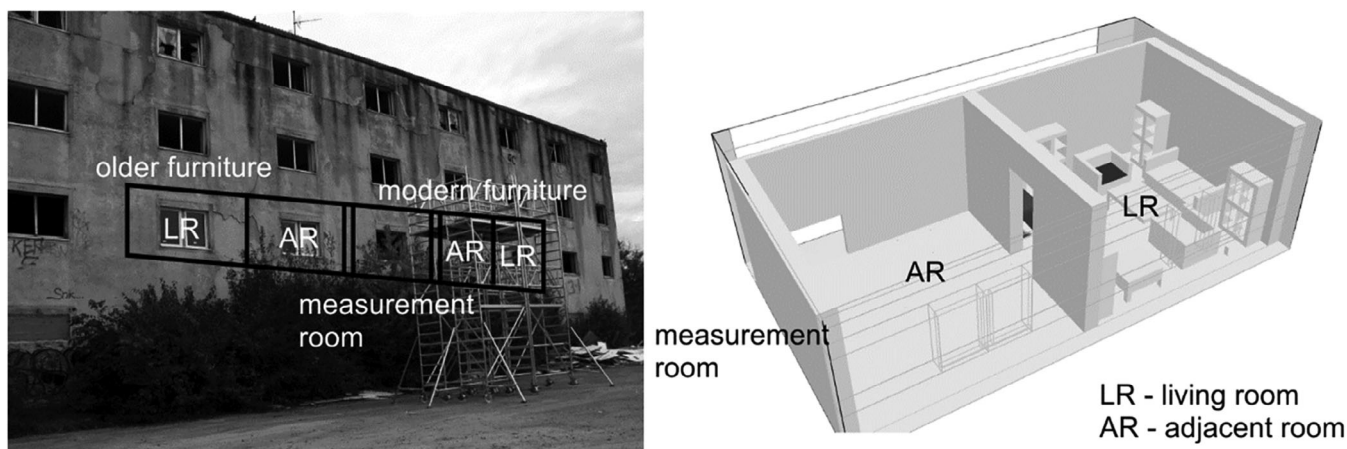


FIGURE 1 Test site, building with two living rooms and two adjacent rooms and one measurement room in the middle (left), living room with adjacent room—schematic (right) [Colour figure can be viewed at wileyonlinelibrary.com]



FIGURE 2 Photos of the two living rooms, with older furniture (left) and with modern furniture (right)⁹ [Colour figure can be viewed at wileyonlinelibrary.com]

first burning item. A similar test series was realised by Steve Kerber (UL, USA) with legacy and modern furniture typical for the United States.⁵

2 | DESCRIPTION OF THE LARGE-SCALE FIRE TESTS IN LIVING ROOMS

2.1 | Test room setup

A series of large-scale experiments was performed with the Frankfurt fire service and BAM as part of the TIBRO project, which was funded

by the German Federal Ministry of Education and Research. In an abandoned apartment complex, two apartments were prepared as fire test site, each of them composed of two ARs connected by a doorway (see Figure 1). One of the rooms was furnished like a common German LR and designated as room of fire origin. The unfurnished AR was included in the experimental setup to assess the temperature and smoke development in the AR additionally to the room of fire origin, Figure 1. In order to investigate the influence of the involved furniture on the fire development, the LR of one apartment was furnished with older furniture (about 30 years old, purchased second-hand, used), the LR of the other apartment with modern furniture (purchased new from a popular Scandinavian furniture store), Figure 2. The fire load was 16.6 kg/m² for the room with modern furniture, and 12.6 kg/m² for the room with older furniture.

For the investigation of the influence of a change in the material composition of furnishings due to the increasing use of materials based mostly on wood and synthetic polymers on the spread fire, the rooms where the fire started were equipped with furnishings typical

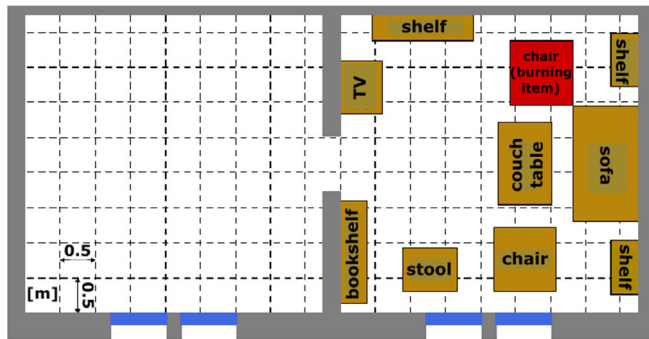


FIGURE 3 Location of the room where the fire started and the location of the furnishings⁹ [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Overview over test series in living rooms

Experimental set-up	Closed windows	Open windows
Living room, older furniture (used)	Experiment 1_1	Experiment 1_2 (one open window)
Living room, modern furniture (new)	Experiment 2_1	Experiment 2_2 (two open windows)

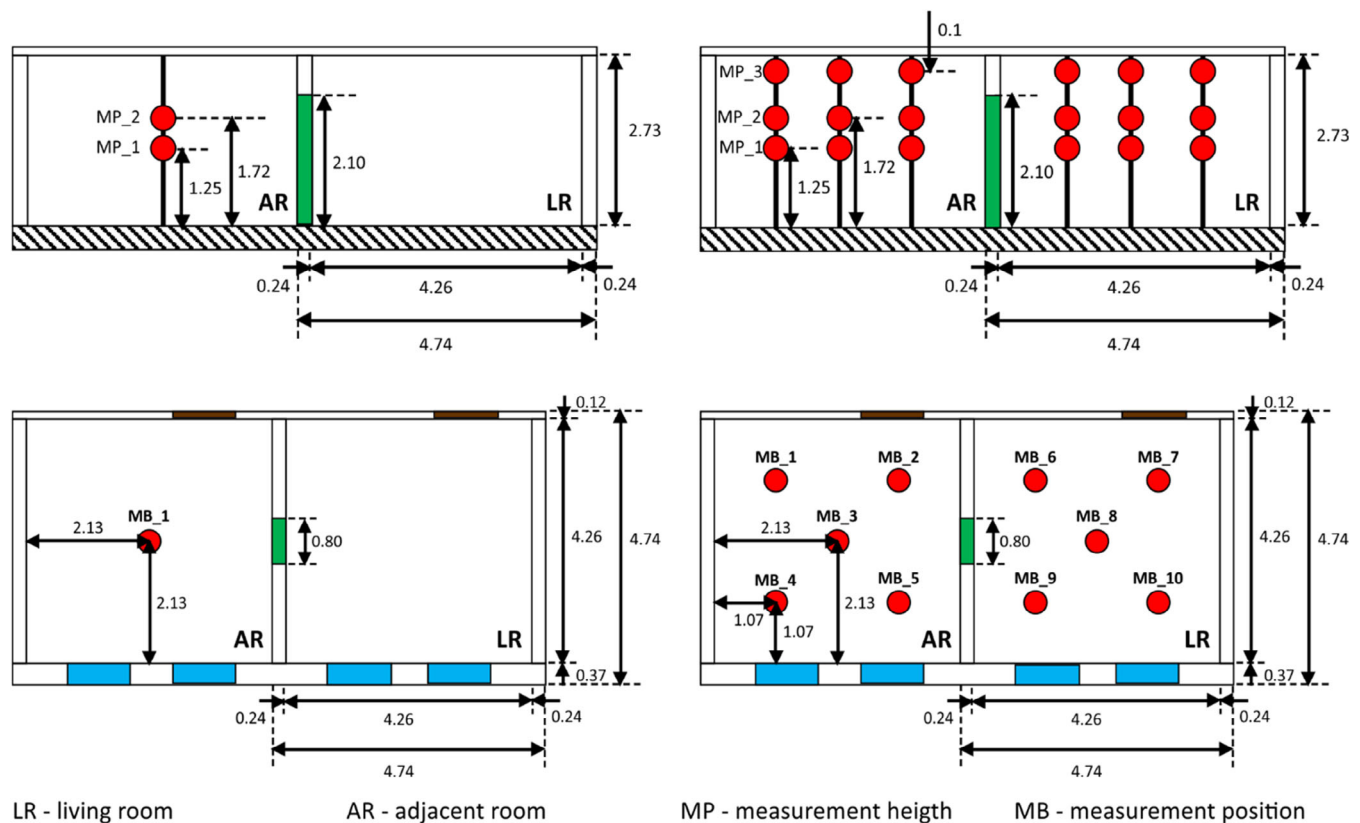


FIGURE 4 Test set-up, location of gas measurements (left hand side) and locations of temperature measurements (right hand side) in vertical projection (top row) and horizontal projection (bottom row) [Colour figure can be viewed at wileyonlinelibrary.com]



FIGURE 5 First burning item: upholstered chair with paper cushion, left hand side: older chair, right hand side: modern chair [Colour figure can be viewed at wileyonlinelibrary.com]

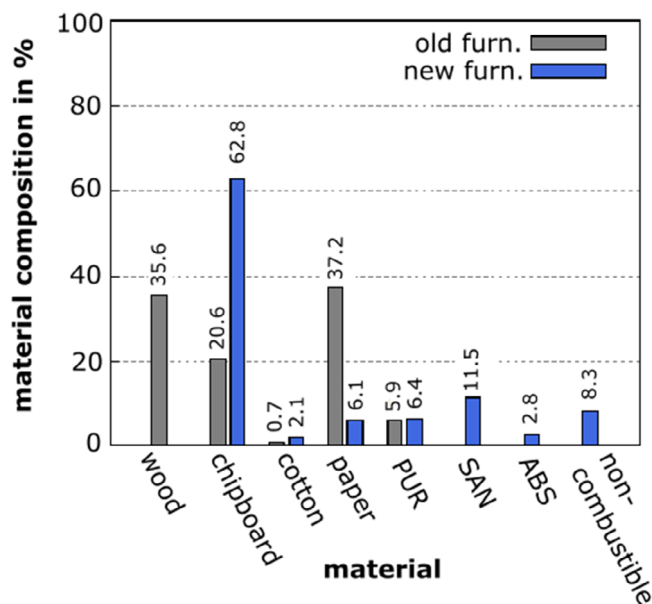


FIGURE 6 Comparison of the material composition of the older (indicated in grey) and modern (indicated in blue) furnishings.⁹ ABS, acrylonitrile butadiene styrene; PUR, polyurethane; SAN, styrene-acrylonitrile [Colour figure can be viewed at wileyonlinelibrary.com]

of German LRs. Type, number, location and total dimensions of the furnishings were kept comparable across all experiments (Figures 2 and 3).

2.2 | Instrumentation

An overview of the measurements and locations is given in Figure 4. Temperatures were measured with mineral-insulated metal-sheathed thermocouples of type K (NiCr-Ni) with an Iconel 600 sheath (TMH GmbH, Maintal, Germany). The thermocouples were of 1.5 mm diameter and had a length of 4 m coupled to 28 m compensation cable. In total, 30 thermocouples were placed at five different locations in the LRs and the ARs in three heights (1.25 m, 1.72 and 2.63 m, which is 0.1 m below the ceiling). Temperatures then were recorded using a Keithley Integra Series Model 2701 Ethernet Multimeter/Data Acquisition System (Keithley Instruments, Inc., Cleveland, Ohio) equipped

with a 40-channel differential multiplexer module model 7708 with automatic cold junction compensation (Keithley Instruments, Inc., Cleveland, Ohio).

Two FTIR spectrometer consisting of a Gasetm DX4000 FTIR gas analyser (Gasetm Technologies Oy, Vantaa, Finland) with a multi-pass sample cell with an optical pathlength of 5 m and an optical resolution of 8 cm^{-1} were used to record spectra of the fire gases at two locations in the test site during the fire tests. One of the FTIR spectrometer (FTIR 1) was operated at 50°C cell temperature and was used more for the qualitative identification of certain expected smoke gas components. Disposable in-line glass fiber filters with a filter porosity of $2\ \mu\text{m}$ (Ansyco GmbH, Karlsruhe, Germany) were used to prevent the intrusion of smoke particles into this spectrometer. The piping system consisted of polytetrafluoroethylene (PTFE) tubes (The cell temperature of the second FTIR spectrometer (FTIR 2) was 180°C). This FTIR spectrometer was further equipped with a portable sampling unit PSS with internal heating (Gasetm Technologies Oy, Vantaa, Finland). The heated piping system consisted of PTFE tubes and was also operated at 180°C . Smoke particles were removed with a heatable prefilter (180°C , stainless steel, filter porosity $3\ \mu\text{m}$) and with a second sintered metal particle filter (stainless steel, filter porosity $0.1\ \mu\text{m}$) located in the portable sampling unit. The data processing and quantitative analysis was done with the analysis software Calcmeter (Gasetm Technologies Oy, Vantaa, Finland) Version 11 for FTIR 1 and Version 12.14 for FTIR 2 using reference spectra of the pure gas components of typical smoke gases. Resolution of FTIR gives information whether two adjacent bands in a spectrum can be distinguished from each other. High resolution shows a distinct location of each band and reduces overlap between bands.

For many applications in gas phase measurement, a resolution of 1 cm^{-1} or less is selected (high resolution). However, high resolution requires longer measurement and computing times. The signal-to-noise ratio gets worse with higher resolution. According to studies by Larjava et al.,¹⁰ a low-resolution FTIR spectrometer offers some useful advantages, especially for applications outside the laboratory, as the signal-to-noise ratio is better, and the measurement speed is faster.

In the ISO 19702 standard, 4 cm^{-1} or better is recommended, but in these experiments CO , CO_2 and HCN were evaluated that are more than 8 wavenumbers apart, so they can also be evaluated quantitatively with the spectrometers used.¹¹

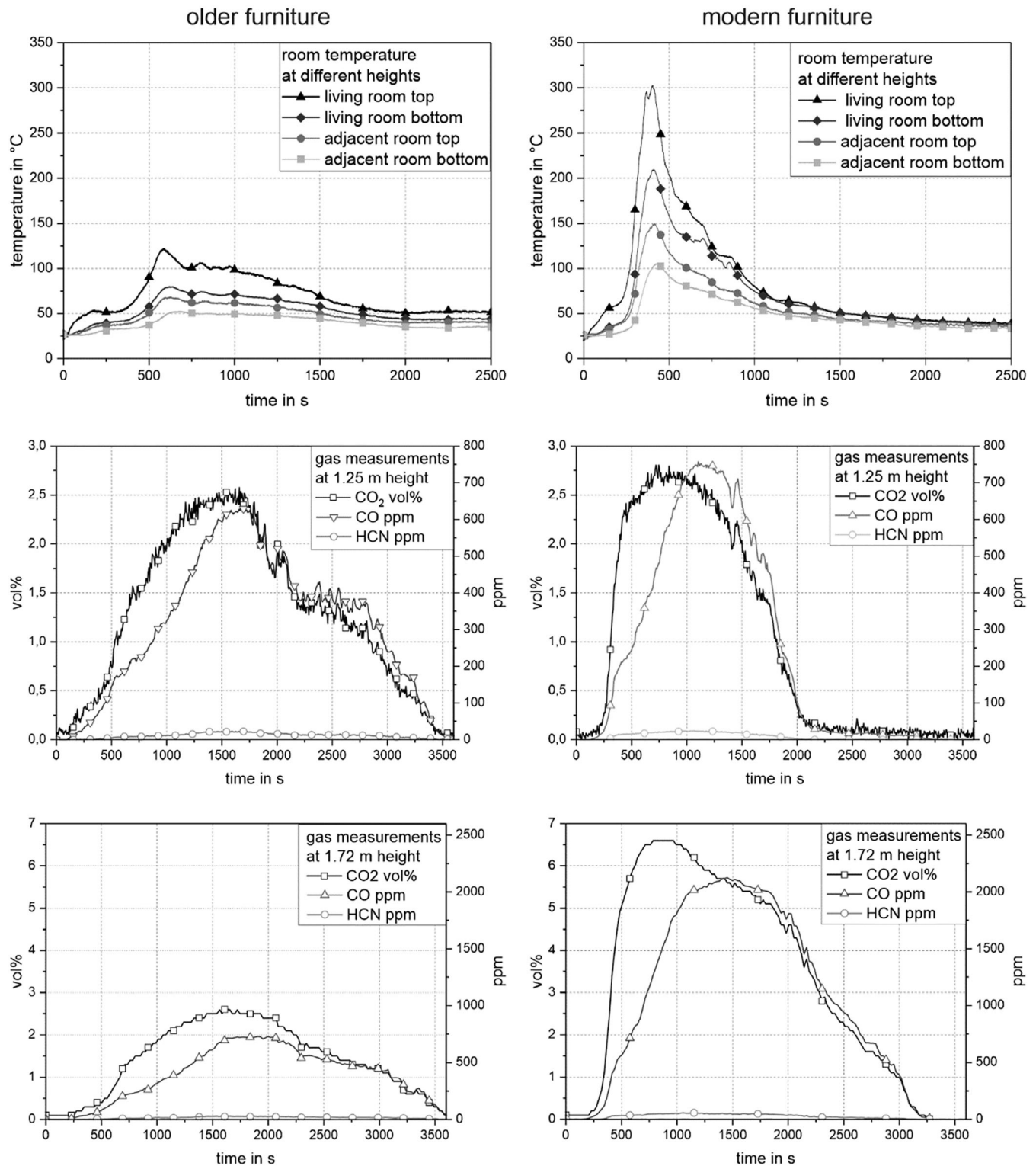




FIGURE 7 Experimental results for the experiments with older (left, experiment 1_1) and modern (right, experiment 2_1) furniture, both with windows closed. Top—average of 5 thermocouples in 2.63 m height, bottom—average of 10 thermocouples in 1.25 and 1.72 m height)

Both spectrometers are calibrated for the evaluated gases. Since the spectrometer with the lower gas cell temperature in the room next to the test room is operated at 1.25 m, the maximum temperatures there were only above 50°C in test 2-2, so that the use of the

spectrometer is seen as justifiable, and also the selected ones Gases CO, CO₂ and HCN are still gaseous even below 50°C. Experience with the technique was gained already in other experiments.^{12,13} Gas measurements were done in the ARs in two different heights (1.25 and

TABLE 2 Visual impressions of experiment 1_1 and 2_2 at 2, 5 and 7 min after ignition taken from video footage [Colour table can be viewed at wileyonlinelibrary.com]

2 min	5 min	7 min	Furnishing/ ventilation
			Old furniture/closed windows
			Modern furniture/ closed windows

1.72 m). The lower measurement location represents the height of a children's head, the higher location represents the height of an adult's head.

2.3 | Test execution

In all four experiments, see Table 1, an upholstered chair was ignited by a burning paper cushion. The paper cushion was a 100-g cushion made of purchased newspaper according to the ignition source used for trains in DIN 5510¹⁴ (with regard to size, style and weight, with the difference that purchased newspaper was used). The older upholstered chair had cushions with polyurethane foam and a viscose textile and a wood frame. Weight of the chair was 31.4 kg with approximately 8.0 kg of polyurethane foam. The older upholstered chair had approximated outer dimensions of 0.8 to 0.8 m wide and 0.7 m high, Figure 5. The modern upholstered chair had cushions with polyurethane foam and cotton textile and a wood frame (beneath the textile). Weight of the chair 58.3 kg with approximately 10 kg of polyurethane foam. The modern upholstered chair had approximated outer dimensions of 1 m to 1 m wide and 0.6 m high.

For the experiment 1_2 with the older furniture, one window was open (in the LR); for the experiment 2_2 with the modern furniture, two windows were open (one in the LR and one additional in the AR). The decision to run the second experiment with modern furniture with two open windows was taken after it became apparent that a main influence of the fire development in the modern furnished room was due to the lack of oxygen. In the older furnished room, the fire did not spread beyond the upholstered chair independent of the ventilation conditions. In the modern furnished room, it was assumed that

spread of the fire beyond the upholstered chair was mainly hindered by lack of oxygen. The fire spread in the second experiment with modern furniture with two open windows confirmed the assumption as the fire developed to a fully developed fire. Each window had a size of 1.1 m to 1.4 m and the door between the rooms had a size of 0.8 m to 2.1 m. Each of the LRs and each of the ARs had a volume of 49.5 m³.

The individual furnishings only differed in their dimensions, individual masses and in their material compositions from one another. The "older" furnishings used in the fire experiments came from the 1960s to 1970s. Their material composition is described below, in Figure 6, as "old furnishings." They were purchased second-hand and were used. The furnishings used in the fire experiments with "modern furniture" came from the present. They were purchased new from a popular Scandinavian furniture store. Their material composition is described below in Figure 6 as "modern." To minimise further material influences, wallpapers and floor coverings were removed from all rooms. The AR was not furnished because only the smoke spread and dispersion was examined for this room.

3 | RESULTS OF THE EXPERIMENTS

In experiments 1_1, 1_2 and 2_1, solely the upholstered chair burned. Only in experiment 2_2, the fire developed further. In Figure 7, the measured temperatures and the measured gas concentrations for the experiments with the older and the modern furniture with closed windows are shown. The temperatures are averaged (m) over the measurement points lying in the hot gas layer and the measurement points lying below the hot gas layer, respectively. Temperatures have

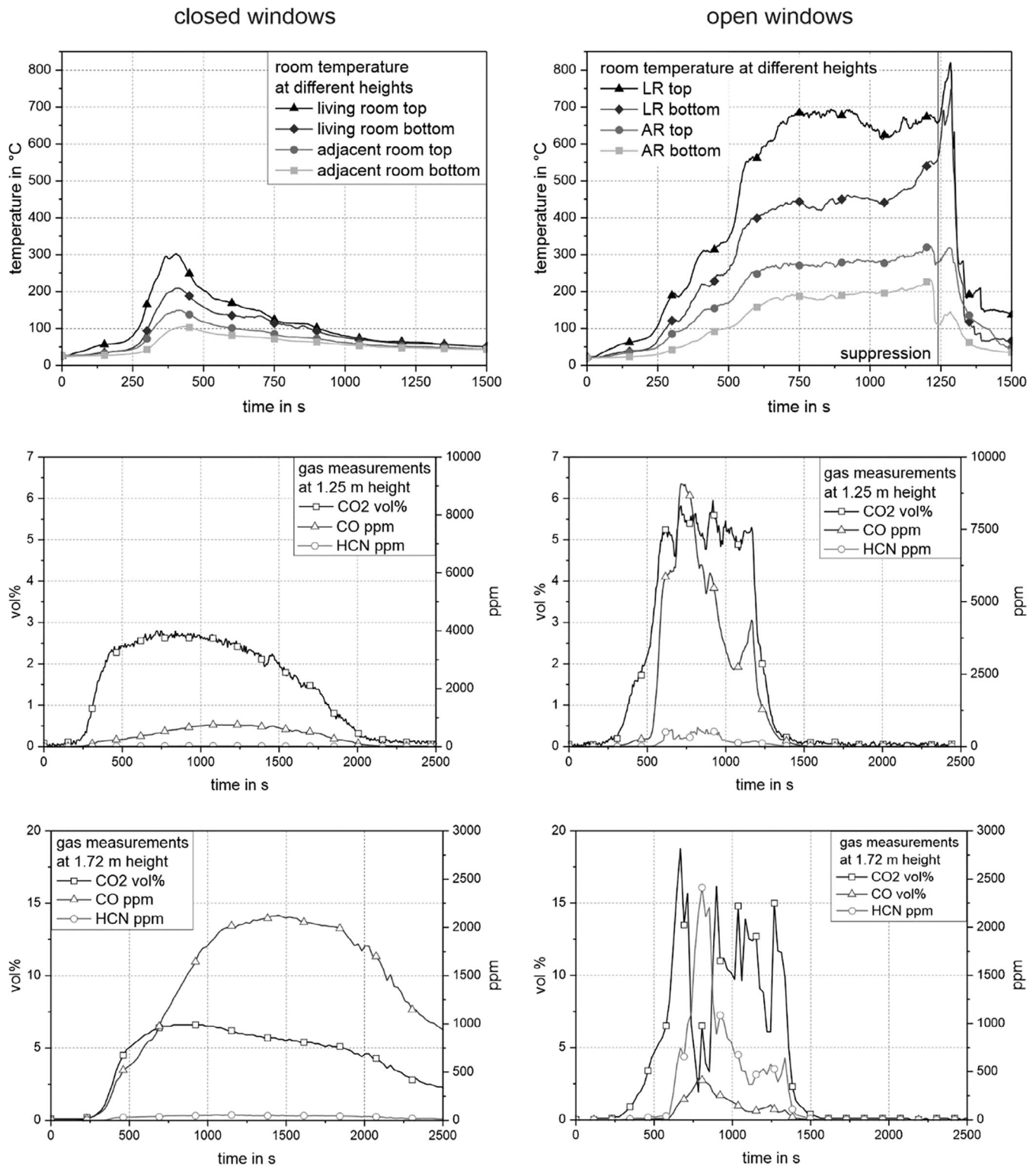


FIGURE 8 Comparison of experimental results for the experiments with modern furniture and windows closed (left, experiment 2_1) and modern furniture with two windows open (right, experiment 2_2), top—average of 5 thermocouples in 2.63 m height, bottom—average of 10 thermocouples in 1.25 and 1.72 m height

been measured in the room of fire origin (LR) and the AR. Smoke composition has been measured in the AR in two heights in the centre of the room, Figure 3.

As can be seen in Figure 7 (top row), the room temperatures in the experiment with modern furniture and closed windows are significantly higher than in the experiment with older furniture and closed

windows. This is true for the room of fire origin and the AR. Maximum temperature in the hot gas layer in the LR for the older furniture is about 125°C, and for the modern furniture about 300°C. After 300 s, the maximum temperature is already reached for the experiments with the modern furniture, and for the experiment with the older furniture the maximum temperature is reached only after 600 s. The gas concentrations of CO, CO₂ and HCN are shown in Figure 7 (centre and bottom row) for the two measured heights (1.25 and 1.72 m) in the AR for the experiment with the older furniture and closed windows and the experiment with the modern furniture and closed windows. The gas concentrations for the 1.25 m height are in the same order for both experiments although the slope is steeper for the experiment with the modern furniture. In 1.72 m height, the gas concentrations are significantly higher in the experiment with modern furniture and closed windows than in the experiment with the older furniture and closed windows, as can also be seen in Figure 7 (bottom row). Table 2 gives a visual impression of the fire development at 2, 5 and 7 min after ignition. Pictures extracted from video recordings.

Experiments with modern furniture and closed and open windows show the influence of ventilation on the fire development. In Figure 8, consequently the experimental results for the LR experiments with modern furniture with closed windows (left hand side) and the two open windows (right hand side) are compared. The maximum temperatures for the experiment with two open windows are above 600°C for the hot gas layer which indicates fully developed fire in the room. The maximum temperatures for the experiment with closed windows are about 300°C. The gas measurements in 1.25 and 1.72 m height in the AR (centre row and bottom row) in the experiment with open windows give significantly higher maximum concentrations of smoke gases (CO₂, CO and HCN are shown), although the first 500 s of both experiments show similar development.

The fire development in the initial period of both experiments (modern furniture and closed and open windows) is similar, which can be seen in the temperature development in the rooms as well, Figure 9. Within the first 400 s of both experiments, the temperature development in the LRs (LR, top—hot gas layer and LR, bottom—cold gas layer) is similar. Only after 400 s, the temperature development is quite different with significantly higher temperatures in the better ventilated experiment (two windows open). In the experiment with the modern furniture and closed windows, only the upholstered chair burned. The fire could not develop further because of the limited ventilation. In the experiment with the modern furniture and two open windows, a fully developed fire occurred that was suppressed by the fire service after 1200 s.

In the series of experiments, the kind of furniture and the ventilation conditions changed the fire development significantly. To assess the influence of modern furniture on the fire development in fires nowadays, the experiment with the older furniture and open window (experiment 1_2) is compared to the experiment with modern furniture and closed windows (experiment 2_1). In the above comparisons, better ventilation led to faster fire developments, which is generally true.¹⁵ However, comparing the experiment with modern furniture and closed windows to the experiment with older furniture and open

windows shows the significance modern materials have on the fire development even when conditions are less prone for fast fire development. The comparison in Figure 10 takes the results of the experiment with older furniture and open window (1_2), which develops faster than with closed windows (1_1), and the results of the experiment with the modern furniture and closed windows (2_1), which developed much slower than the experiment with the modern furniture and open windows (2_2).

Although the experiment with the older furniture is better ventilated than the experiment with the modern furniture, the temperatures in the LRs and ARs are lower for the older furniture than in the experiment with the modern furniture, Figure 10 (top row). The maximum measured values for the gas measurements (CO₂, CO and HCN) are in the same range for the measurements in 1.72 m height (bottom row). For the measurements in 1.25 m height, the maximum values for the older furniture are higher, but the slope of the measured gas concentrations is higher for the modern furniture experiment in the beginning of the experiments. The plots in Figure 11 are an expansion of the data from Figure 10, and they only show the first 600 s of the tests.

Figure 11 shows the comparison between the gas measurements in the experiment with the older furniture and the open window (1_2) and the experiment with the modern furniture and closed windows (2_1) for 1.25 m height and 1.72 m height for the first 600 s. For both heights, the measured gas concentrations of CO, CO₂ and HCN are higher for the modern furniture (solid lines with full symbols in Figure 11), especially for the higher measurement position. After 600 s, the CO₂ concentration at 1.72 m height is six times higher, the CO concentration is four times higher and the HCN concentration is three times higher for the experiment with modern furniture than in

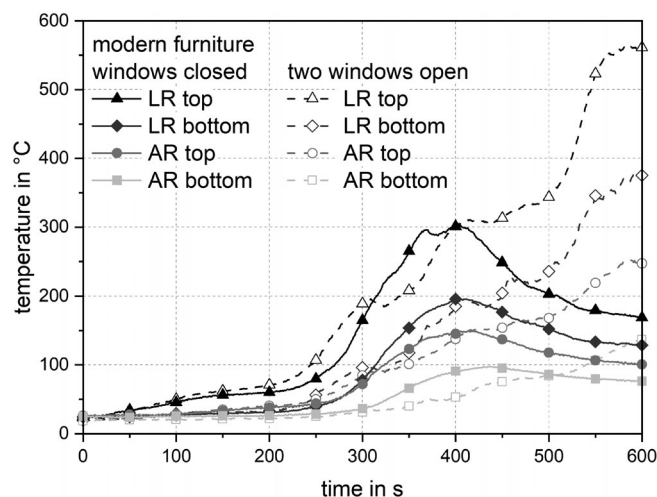


FIGURE 9 Comparison of temperatures for the living rooms and adjacent rooms for the experiments with modern furniture with closed and open windows (experiments 2_1 and 2_2) for the first 600 s of the tests (LR—living room; AR—adjacent room; top—average of 5 thermocouples in 2.63 m height; bottom—average of 10 thermocouples in 1.25 and 1.72 m height; 1—experiment 2_1; 2—experiment 2_2)

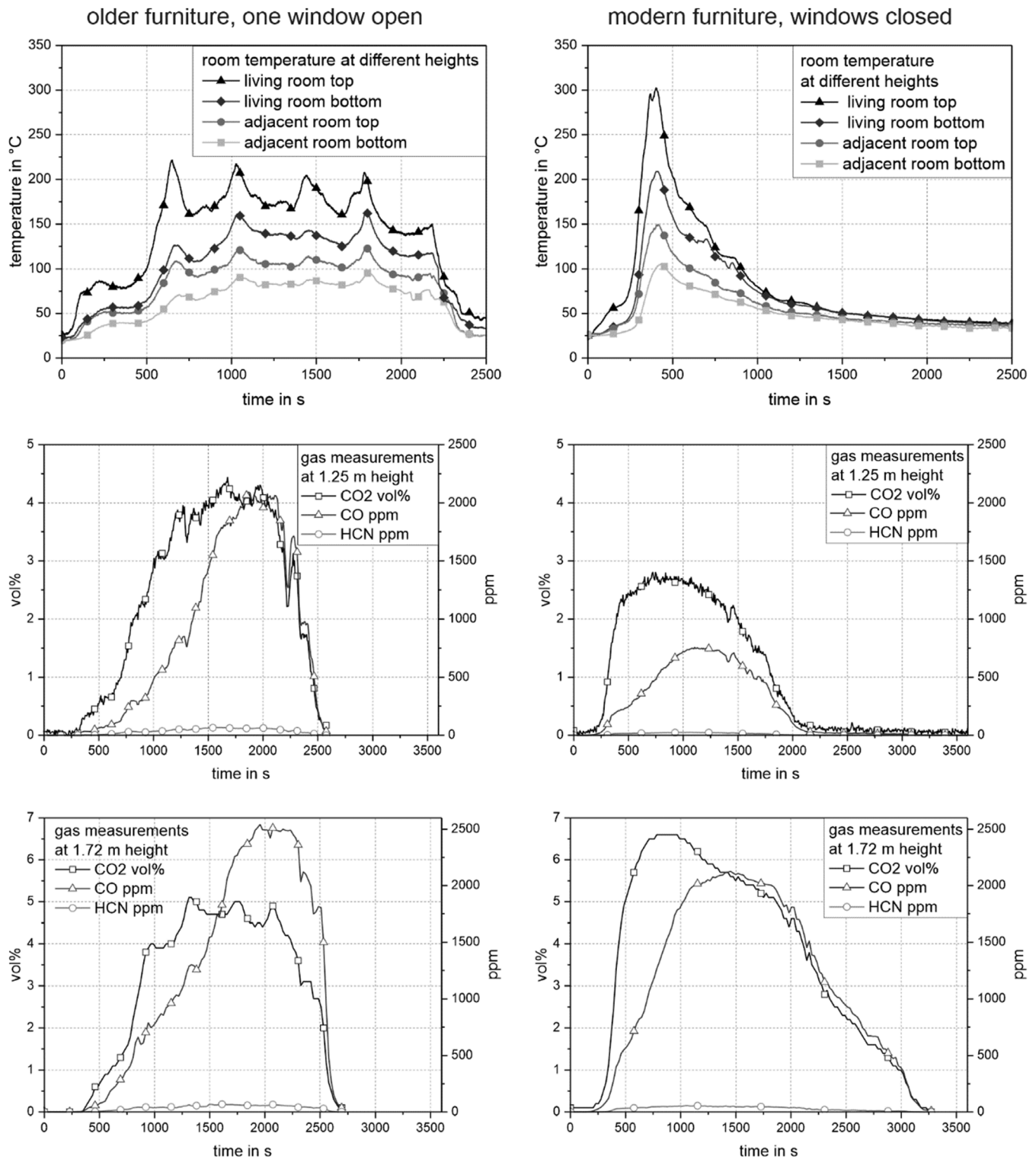


FIGURE 10 Comparison of experimental results for the experiments with older furniture and one window open (left, experiment 1_2) and modern furniture and windows closed (right, experiments 2_1), top—average of 5 thermocouples in 2.63 m height, bottom—average of 10 thermocouples in 1.25 and 1.72 m height

the experiment using the older furniture. The increase in measured gas amounts in the AR starts approximately 100 s earlier in case of modern furniture than for the older furniture.

Photographs taken after the fire tests are shown in Figure 12. The damage in the room with modern furniture is obviously much higher than in the room with older furniture.

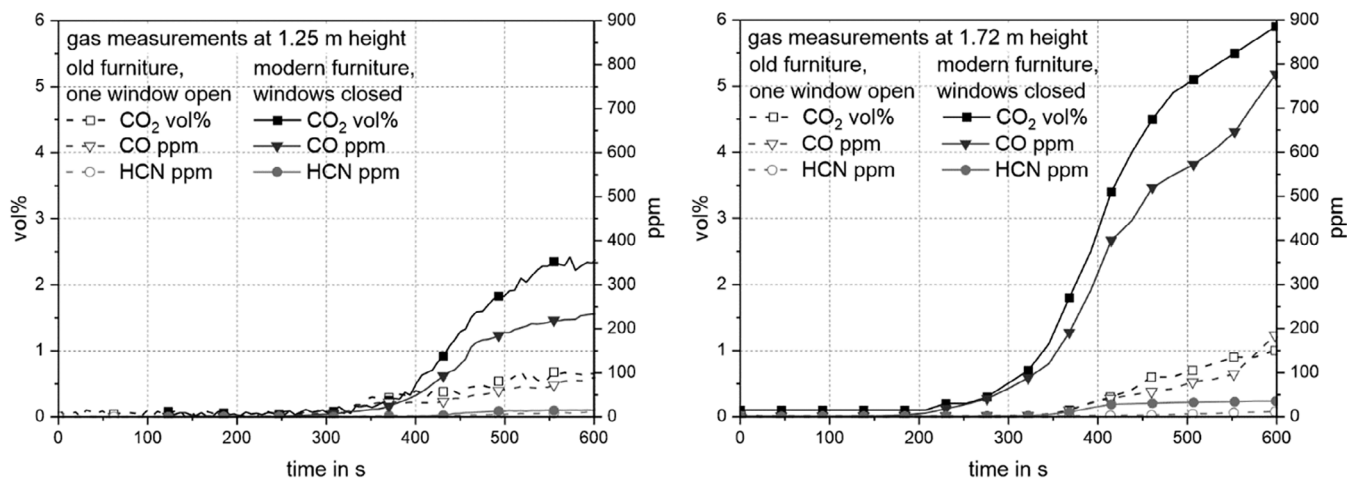


FIGURE 11 Comparison of gas measurements in 1.25 m height (left) and 1.72 m height (right) for the experiments with older furniture and one window open (experiment 1_2) and modern furniture and windows closed (experiment 2_1) for the first 600 s of the respective experiment



FIGURE 12 Living room with older furniture (left), with modern furniture (right) after the fire tests [Colour figure can be viewed at wileyonlinelibrary.com]

For the further analysis of the influence of the ventilation, the volume ratio of CO to CO₂ was calculated for all four experiments from the gas concentrations derived from the FTIR measurements. Figure 13 depicts the development of the CO/CO₂ ratio throughout the whole experiments for both heights (1.72 and 1.25 m). As these are the measurements in the AR and not in the room of fire origin, the results can be considered of less significance and only give an indicative result of the conditions in the AR and not in the room of fire

origin. For both furniture sets, in case of the experiments with closed windows, the ratio stays below 0.05, which is described for well ventilated conditions.¹⁶ Even in case of the fire test with the old furniture and one window open, the ratios rise only up to 0.08, which might be above 0.05 for well-ventilated conditions, but is still below 0.2, above which the conditions are considered under-ventilated. Only in case of the modern furniture with both windows open, the ratio of CO to CO₂ rises well above these thresholds up to a ratio of 1.5.

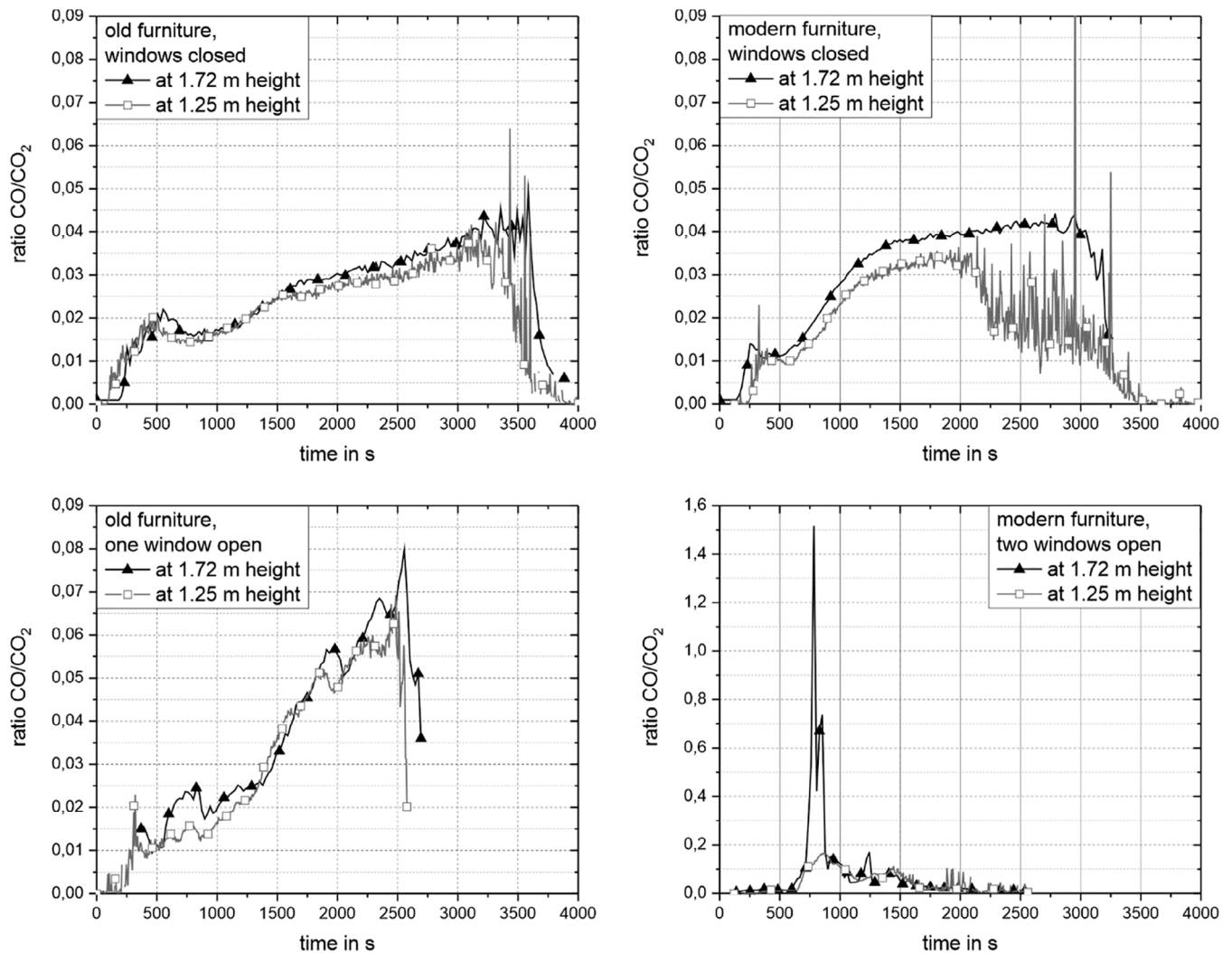


FIGURE 13 Comparison of the ratio of CO to CO₂ in the adjacent room at 1.72 m height (black lines with solid symbols) and at 1.25 m height (grey lines with open symbols) for all experiments: with older (left) and modern (right) furniture and windows closed (top) and windows open (bottom)

4 | CONCLUSIONS

A series of four large-scale experiments in LRs with ARs have been performed. In two experiments older furniture has been used, and in two experiments modern furniture has been used. The ventilation conditions have been varied by windows. Two experiments have been performed with closed windows to compare the fire development between the older and the modern furniture. In all experiments, mainly the first ignited upholstered chair burnt. Only, in the experiment with modern furniture and better ventilation, the fire developed further and involved other furniture of the room as well. The temperatures of the upper layer in the room of fire origin was in experiments with old furniture below 250°C for all times; therefore, ignition of further items even in the region of the upper layer was not likely. Generally, in the experiments with modern furniture, the fires developed significantly faster than the fires with older furniture and produced

higher concentrations of smoke gases and higher temperatures in the room of fire origin and the AR. In the room of fire origin and the AR, the maximum temperatures were reached after about 300 s for the modern furniture and only after 600 s for the older furniture. Also, the concentration of smoke gas components as CO, CO₂ and HCN rises much faster for the modern furniture fires. In both experiments with modern furniture, 300°C were reached in the upper level of the room of fire origin; therefore, ignition of further items becomes more likely for the modern furniture.

The fire develops into a fully developed fire in the experiment with modern furniture and two open windows. For the first 400 s of both experiments with modern furniture, fire development was similar. After 400 s, the room temperature in the experiment with open windows rises significantly higher than in the experiment with the closed windows: The maximum temperatures are about 700°C for the open windows and about 300°C for closed windows. Also, the smoke

gas concentrations in the AR are similar for the first 400 s of both experiments. After 400 s, the smoke concentrations of the open window experiment exceed the concentrations of the closed window experiment. However, even with closed windows the CO concentrations within the first 400 s of the test are very high.

The faster fire development caused by modern furniture becomes even more apparent when the experiment with older furniture and one open window is compared with the experiment with modern furniture and closed windows. Although the fire is more ventilated in the experiment with the older furniture the maximum temperatures in the experiment with the modern furniture are distinctly higher than in the experiment with the older furniture. The smoke gas concentrations are significantly higher for the first 600 s of the experiments for the modern furniture fire.

ACKNOWLEDGEMENTS

We thank the Frankfurt fire service for their technical support and for providing the test facility, without the input of the Frankfurt fire service the tests would not have been possible to perform. The tests were run as part of the TIBRO project, which was funded by the German Federal Ministry of Education and Research (BMBF) with funding reference 13N12176.

DATA AVAILABILITY STATEMENT

Data available on request from the authors

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How to cite this article: Hofmann A, Klippel A, Gnutzmann T, Kaudelka S, Rabe F. Influence of modern plastic furniture on the fire development in fires in homes: large-scale fire tests in living rooms. *Fire and Materials*. 2021;45:155-166. <https://doi.org/10.1002/fam.2934>