A NEW APPARATUS FOR FLAME SPREAD EXPERIMENTS

Johan Mangs

VTT Technical Research Centre of Finland, Espoo, Finland

ABSTRACT

In fire PRAs (*p*robabilistic *r*isk *a*nalyses) for nuclear power plants, flame spread on solids, especially cables, is a significant scenario, and studies on flame spread are central issues in research projects on fire safety of nuclear power plants at VTT. As one of the results, a new flame spread measuring instrument was proposed. A two-meter vertical sample test rig has been built for the measurement of flame spread velocity as a function of initial temperature. It had been observed in flame spread experiments, that at some distance above the point of ignition, flame spread was approaching constant velocity. Sample length two meters was estimated to be enough to reach this state. In the new rig, the sample is heated to desired temperature before ignition with a small propane burner, and flame spread is monitored with thermocouples close to the sample surface. This paper describes features and function of the test rig, and vertical flame spread experiments on cylindrical birch wood samples and on cable samples.

INTRODUCTION

Studies on flame spread, the biggest unsolved problem of fire science, was a central issue in VTT research project POTFIS (*Pot*ential of *fi*re *s*pread), and followed by FIRAS (Implementation of quantitative fire risk assessment in PSA). The approach was to carry out interactively modeling, numerical simulation and experimental work on the relevant, most promising simple solid fuel scenarios for qualification and validation of specific models [1], [2], and [3].

One of the results was a proposal for a new flame spread measuring instrument: a 2 m vertical sample test rig for the measurement of flame spread velocity as a function of initial temperature. In flame spread experiments, it was noticed that at some distance above the point of ignition, flame spread was approaching constant velocity. A sample length of 2 m was estimated to be enough to reach this state.

The purpose is to obtain a continuous preheated air supply throughout the experiment to be able to measure flame spread velocity at different initial temperatures, starting from ordinary room temperatures up to temperatures near auto-ignition level, maximum 400 ^{o}C. Thermocouples close to the sample surface indicate flame front propagation along the sample.

Operating principles, structure and materials for the new instrument were presented to fine-mechanical workshop Protoshop Oy, where detail design and construction was carried out in close co-operation with VTT. The 2 m test rig was completed in summer 2007, and start-up tests were initiated at VTT. A detailed presentation of the system is given in [4]. This report summarizes features and function of the test rig, and four series of vertical flame spread experiments on cylindrical birch wood samples and on *p*oly*v*inyl *c*hloride (PVC) and *f*lame *r*etardant *n*on-*c*orrosive (FRNC) cable samples.

REALIZATION OF THE APPARATUS

The structure of the test rig is shown in Figure 1. The device consists of a heating channel and a test channel (width 300 mm, depth 330 mm), separated from each other by a thin stainless steel sheet and connected to each other at the upper and lower parts of the channels. The device is insulated with 100 mm thick Kaowool layer between 0.5 mm stainless steel plates. There is a door on the front side to the channels, an air inlet in the upper part of the heating channel and a smoke outlet at top of the test channel. The device is pivoted to a massive steel support at its lower end, and can be used in either vertical or horizontal position. This report considers operation in vertical position only.

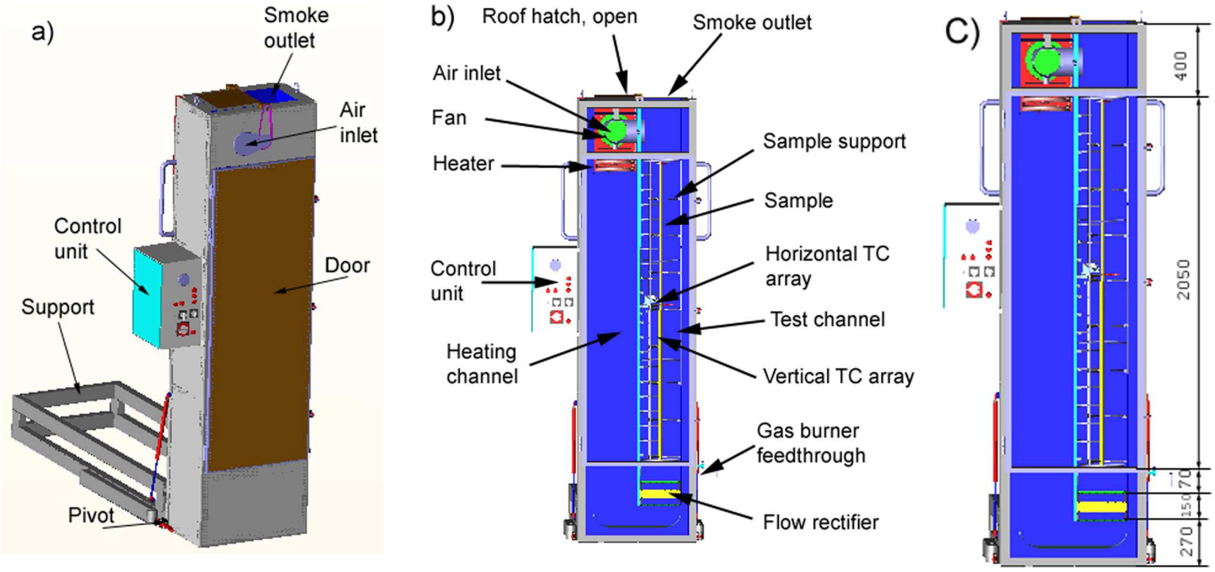


Figure 1 2 m test rig in vertical position; a) general view, b) cross-section with essential features, c) vertical dimensions in mm

Air is heated with a 7.0 kW heating resistor and is circulated with a fan located in the upper part of the heating channel. In the heating phase the air inlet and roof hatches are closed and air is circulated within the cabinet (Figure 2 a), heating the sample. During the flame spread experiment the fan draws in fresh air through the intake in the upper part of the heating channel, onwards through the heater to the test channel, and fire effluents exit through the outlet (Figure 2 b), with the upper opening connecting the channels closed. Control functions such as rate of air flow and temperature are located in a control unit on the outside of the cabinet.

The maximum heat release rate from samples in the cabinet can be estimated, starting from the heat release density of solids (100 … 200 kW/m^2) and oxygen consumption calorimetry (2.94 MJ/kg of dry air), to remain below 100 kW (mostly below 20 kW), which would mean average vertical air flow velocities smaller than 0.3 m/s (mostly below 50 mm/s).

Air should circulate to some extent during heating to avoid damage to the resistors. A minimum flow rate of 0.3 m/s was suggested. This air flow should provide sufficient oxygen for burning during the experiment. The flow rate of 0.3 m/s corresponds to a volumetric flow rate of 30 dm^3/s in the 0.3 m x 0.33 m channel.

The air flow into the test channel is straightened with a flow rectifier consisting of two 1 mm steel wire screens above and below a honeycomb, with cell length 50 mm and diameter 5 mm.

The 2 m long sample is suspended from its upper end in a support and kept in place in the centre of the test channel with pins at 250 mm vertical intervals. Vertical gas temperatures are measured at 100 mm vertical intervals with 0.25 mm K-type thermocouples T1 ... T19 supported by ceramic insulator tubes shielded with steel tubes.

The sample is ignited from below with a helical shaped propane burner and a glow wire.

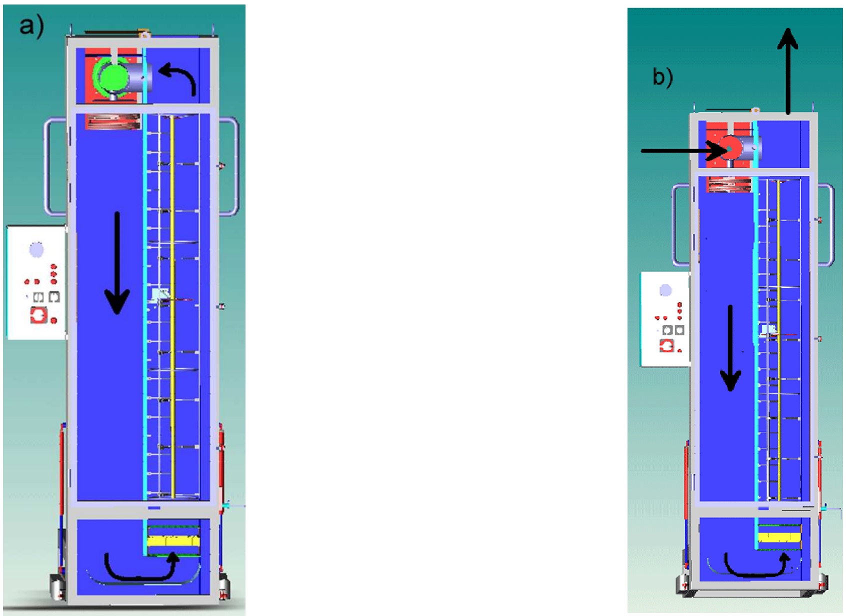


Figure 2 a) circulation of air during heating phase, b) fresh air intake to heating channel and fire effluent outlet from top of test channel during experiment, upper opening connecting the channels closed

VERTICAL FLAME SPREAD EXPERIMENTS

Flame spread experiments were carried out on cylindrical birch wood samples, PVC and FRNC cables. Cables are presented in Table 1 and essential experimental features in Table 2.

Table 1 Cross-sections and structures of cables in flame spread experiments; scale in mm

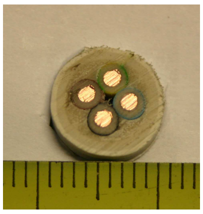
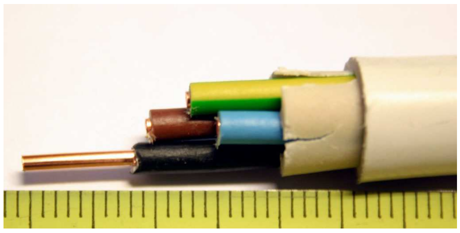
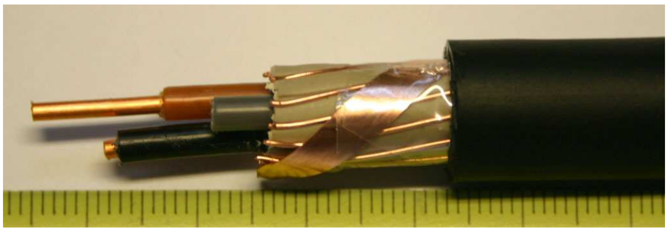
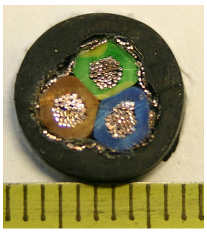
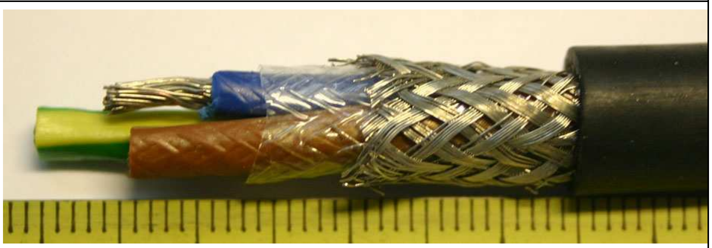
Cable	Cross-section	Structure
PVC cable MMJ 4 x 1.5 mm^2		
FRNC cable N2XCH 3 x 2.5 mm^2		
FRNC cable HXELCHXÖ 3 G 2.5 mm^2		

Table 2 Essential features in flame spread experiments

Sample	Sample diameter [mm]	Temperature range [°C]	Burner power output [W]	Burner duration [s]	Flame spread range [mm/s]
Birch wood	8	22 ... 271	200...250	55 ... 97	6.4 ... 61.5
MMJ 4 x 1.5 mm^2	9.5	22 ... 187	400...600	130 ... 260	2.6 ... 8.4
N2XCH 3 x 2.5 mm^2	13	22 ... 293	550...650	644 ... 810	0 ... 3.6
HXELCHXÖ 3 x 2.5 mm^2	9	22 ... 294	540...600	265 ... 1235	0 ... 6.5

In the heating phase, the sample was heated with air circulating at highest possible speed, 2.6 m/s air flow at room temperature in the test channel. Times to reach desired temperature varied from 9 min to reach an average temperature of 90 °C to 65 min to reach 293 min. When the desired temperature was reached, transition from heating phase to flame spread experiment consisted of the following sequence:

1. Reaching desired temperature, heating was temporarily turned off.
2. The air flow was lowered to 0.3 m/s air flow.
3. Heating was turned on.
4. The heating of glow wire was turned on.
5. The propane gas line was opened.
6. Burner ignition and sample in flame contact.
7. The roof hatch was opened.

Maximum gas temperatures T_{max} in the test channel were measured immediately before turning heating temporarily off and lowering air flow rate. After this the temperatures decreased somewhat to T_{ign} until ignition of the burner and the sample, as seen from the measured temperature–time curves (Figure 3a). The temperature in the test chamber varies somewhat with vertical height (Figure 3b). The temperature of the flame spread experiment is denoted T_{ave} and calculated as the average temperature in the test channel immediately before turning the burner on.

The propane burner was on until the thermocouples showed that the sample had ignited and flame spread was established. Burner flame durations and burner power output are given in Table 2.

Rate of flame spread is deduced from temperature measurements, which requires some flame spread criterion related to the measured temperature curves. Visual inspection of the temperature-time curves indicated that around 300 °C the temperature rise is steep for most of the curves. The propagation of flame front to a certain height was thus estimated by determining the moment when the corresponding thermocouple indicated temperature rise above 300 °C.

Plotting this height of flame spread as a function of time one notes that after some time (length of burning) the flame spread approaches constant velocity. A straight line is then fitted to this part of the curve, giving rate of flame spread as the slope of the line (Figure 3c). The possible influence of the choice of 300 °C as a flame front propagation criterion was checked for some experiments using times for reaching 400 °C as criterion. The straight line fittings gave the same slope.

Physical and chemical changes occur in the sample during heating before ignition, and this was monitored with a 100 ... 175 mm long reference sample located 0.9 m above lowest TC level and at 100 mm horizontal distance from the sample. The reference sample was weighed before and after the experiment, giving an indication of changes due to heating.

RESULTS FROM EXPERIMENTS

During the heating phase data acquisition was performed at a rather slow rate, e.g. at 60 s intervals, and the rate was changed to 1 s interval some minutes before the flame spread experiment is started. Origin of time scale in the figures refers to the moment of this change.

Examples of temperature-time curves, vertical temperature distributions in the test channel, and determination of rate of flame spread from an experiment on a cylindrical birch sample are presented in Figure 3a to Figure 3c. Relative mass loss of reference sample as a function of maximum gas temperature measured with thermocouple T10 near the reference sample is presented in Figure 3d.

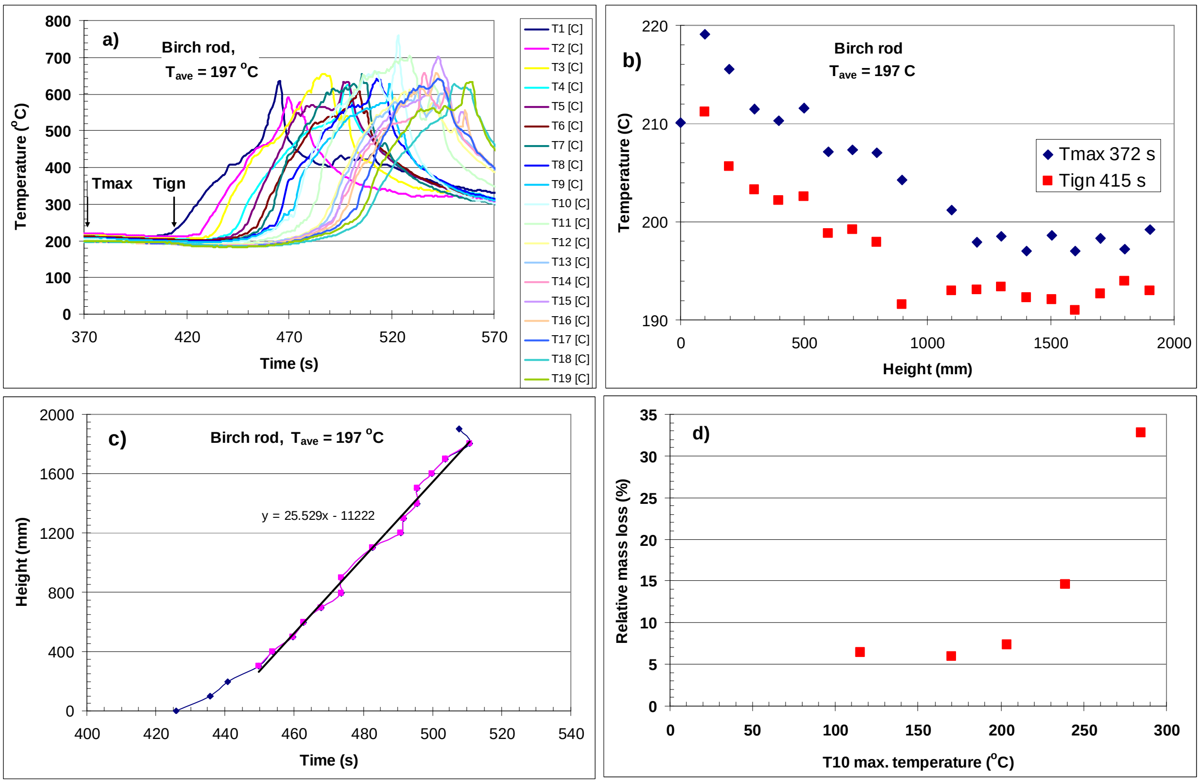


Figure 3 Flame spread on a cylindrical birch sample. a) temperature-time curves, T_{max} and T_{ign} indicated with arrows, b) vertical temperature distribution at times for T_{max} and T_{ign}, c) straight line fit to height – time plot, criterion: time when T > 300 °C, c) relative mass loss including moisture from reference birch samples

The rate of flame spread as a function of T_{ave} for birch wood samples is presented in Figure 4 and for cable samples in Figure 5. "Error bars" on the right of the markers indicate T_{max}.

The birch wood samples were stored in ordinary indoor conditions (moisture content 5 ... 6 mass-%). The samples marked "not dried" were inserted into the test channel after which heating to desired temperature started. For these samples, moisture content varied between 5 ... 6 % for experiments at room temperature to approximately 2.5 % after heating, estimated from moisture-time curves for a similar piece of wood drying in an oven. Samples marked "dried" were dried for about 4 hours at 110 °C in the 2 m apparatus before the experiments.

The specimen in the new apparatus is in a rather narrow channel with a small airflow upwards during the experiment. In order to check whether this has an influence on rate of flame spread, Figure 4b presents a comparison between flame spread results obtained in the 2 m apparatus and results obtained with a similar set-up in free space without boundaries [5], all experiments at room temperature. Experiments in free space were carried out with 0.8 m long birch rods differing in diameter, which had been dried in an oven, assembled in the test rack and ignited. During this procedure sample moisture was estimated to be 1 %. Rate of flame spread was deduced from T > 300 °C criterion in all cases. Results from 2 m apparatus are from both dry samples and ~ 6 % moisture samples. Free space results (1 % sample moisture) set between these points in a logical way and the influence of the 2 m apparatus environment seems not to be significant.

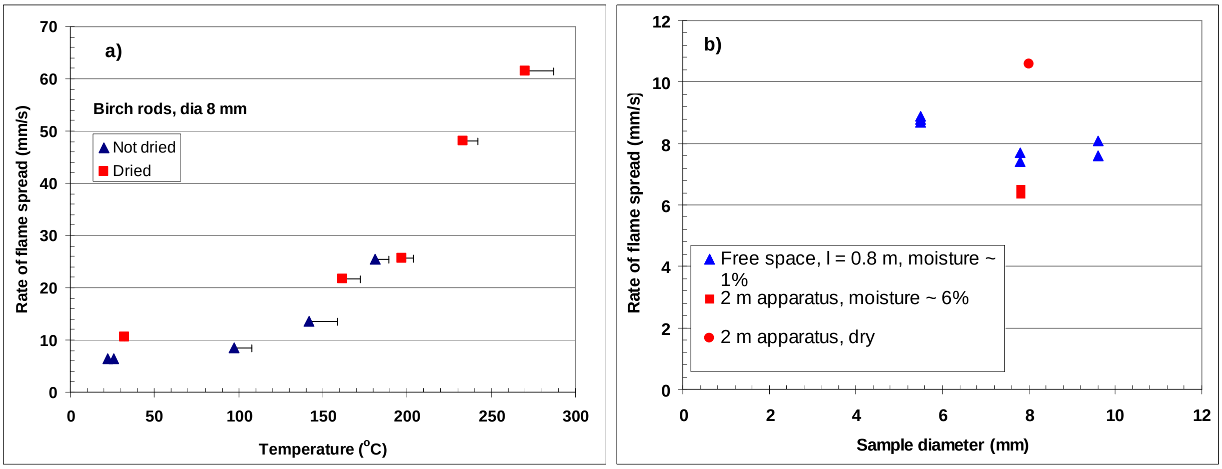


Figure 4 a) rate of flame spread on 8 mm birch rod samples, b) comparison between flame spread rate on birch rods measured in free space and in the 2 m apparatus

PVC cable MMJ ignited and burned to full length in all experiments (Figure 5a). The MMJ series was not continued above 200 °C as the cable material softens and does not remain stiff enough to be in proper place during the experiment. FRNC cable N2XCH ignited and burned to full length in all experiments where initial temperature was 90 °C or higher. (Figure 5a) The sample ignited at room temperature 22 °C and fire spread up to 1 m height. No flame spread was observed in an experiment at 82 °C. FRNC cable HXELCHXÖ ignited and burned to full length in experiments with initial temperature 193, 248 and 294 °C. No flame spread was observed in the other HXELCHXÖ experiments. In two of the HXELCHXÖ experiments the straight line was fitted separately to the start and end part of the height-time plot as one single line seemed not feasible, and correspondingly two flame spread rate values are shown in Figure 5b. Figure 5c demonstrates the situation for experiment T_{ave} = 193 °C, where the size of the flame was clearly smaller at 1700 ... 1800 s than at the end of the experiment, as observed visually from above through the smoke outlet This is also seen in Figure 5c as a slower flame spread at this time. Figure 5c also shows straight line fits using both T > 300 °C and T > 400 °C criterion giving the same slope. Figure 5d presents the reference sample loss in the FRNC cable experiments indicating changes in the samples starting at temperatures somewhat below 200 °C.

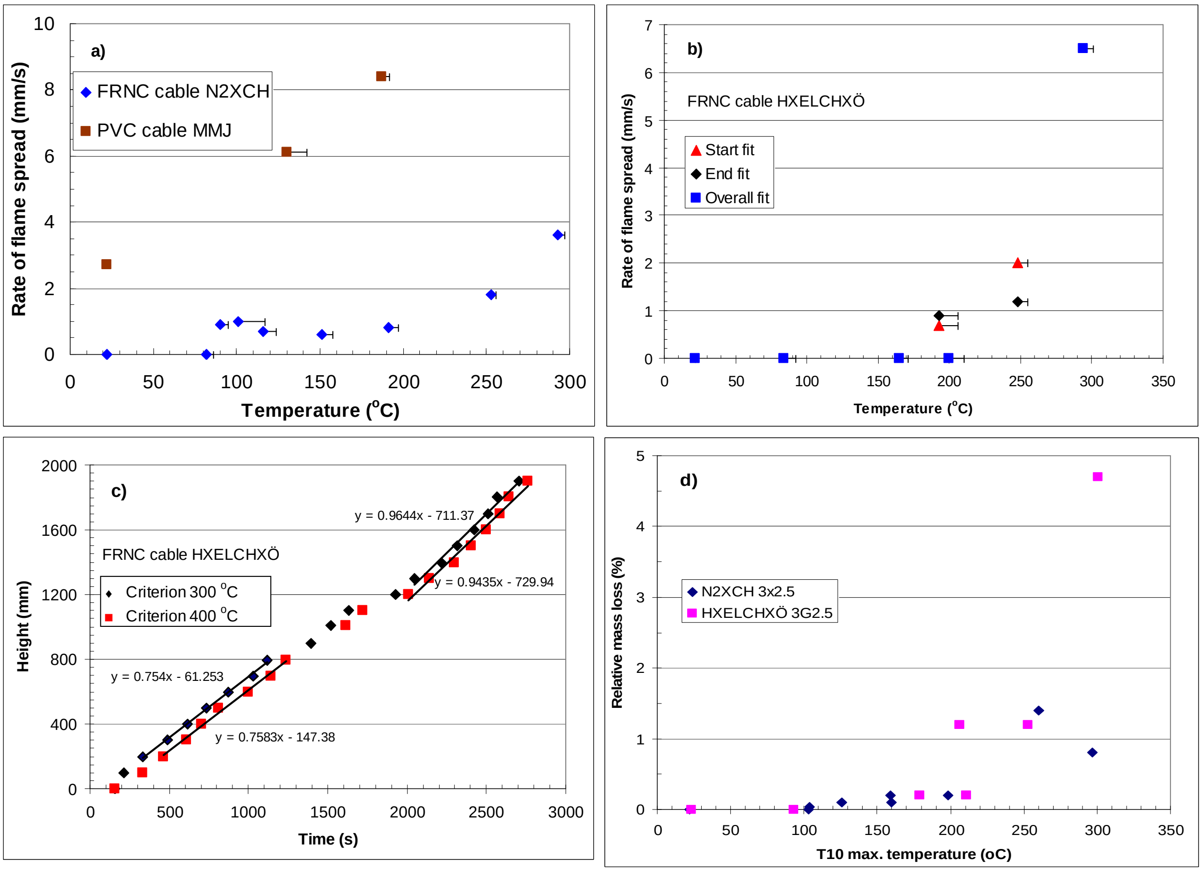


Figure 5 a) and b) rate of flame spread on PVC and FRNC cables, c) uniformity of rate of flame spread determined with two temperature criteria, separately for start and end of experiment, d) reference sample loss in FRNC cable experiments

CONCLUSIONS

Features and function of a new apparatus for measuring flame spread on vertical samples at different initial temperatures are presented together with flame spread experiments on wood and cable samples, differing both in materials and structure.

The rate of flame spread on wood samples was 6.4 ... 61.5 mm/s in a temperature range 22 ... 271 °C, on PVC cable samples 2.6 ... 8.4 mm/s in a temperature range 22 ... 187 °C and on two FRNC cable samples ~ 1 ... 3.6 mm/s and ~ 1 ... 6.5 mm/s in temperature ranges 90 ... 293 °C and 193 ... 294 °C, respectively. Flame spread did not occur or spread only to part of the FRNC cable sample in lower temperatures. The rate of flame spread dependence on temperature seems to be roughly exponential for both birch wood and cable samples.

Symmetrical flame propagation around the sample is essential as temperature measurements are only in one vertical rake. At least for samples of diameter as in these experiments this requirement was fulfilled as viewed from above.

The new flame spread apparatus seems to be appropriate for determining vertical flame spread as a function of temperature.

ACKNOWLEDGEMENTS

This work has been partially funded by the State Nuclear Waste Management Fund (VYR) and STUK - Radiation and Nuclear Safety Authority Finland. Protoshop Oy is acknowledged for detail design and construction of the apparatus.

REFERENCES

[1] Hostikka, S., and O. Keski-Rahkonen, "Simulation of vertical flame spread by FDS in DNS mode – Numerical excursions into flames for designing physical experiments and guiding engineering modeling", Research Report VTT-R-00567-07, 56 p., 2007

[2] Keski-Rahkonen, O., and J. Mangs, "Assessing of flame spread on NPP cables", Y. Zhou, S. Yu & Y. Xu (eds.), Proceedings of the 18th International Conference on Structural Mechanics in Reactor Technology, SMiRT 18, Beijing, China, August 7–12, 2005, Atomic Energy Press. Beijing, Pp. 3972–3983, 2005, www.iasmirt.org

[3] Keski-Rahkonen, O., and J. Mangs, "POTFIS project special report – Experiments and modelling on vertical flame spread", In: Räty, H. & Puska, E. K. (ed.), 2004, SAFIR, The Finnish Research Programme on Nuclear Power Plant Safety 2003–2006, Interim Report, VTT Research Notes 2272, VTT Processes, Espoo. Pp. 257–265, ISBN 9513865150; ISSN 12350605, 2005, http://virtual.vtt.fi/inf/pdf/tiedotteet/2004/T2272.pdf

[4] Mangs, J., "A new apparatus for flame spread experiments", VTT Working Papers 112, Espoo, 2009, 51 p. + App. 28 p., http://www.vtt.fi/publications/index.jsp

[5] Mangs, J., O. Keski-Rahkonen, and S. Hostikka, "Vertical flame spread. Development of and experiments on small and medium scale test rigs", VTT Building and Transport, POTFIS 1.1 + 2.1 work report for year 2005 (internal unpublished report), 110 p., 2006