

Opposed flame spreading along a structured PMMA sample in exploration atmosphere under microgravity

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As part of SAFFIRE V experiments on the ISS supply spacecraft CYGNUS, flame propagation along different surface structures on a PMMA sample was investigated in opposed flow. The sample was 200 x 400 mm (length x width) with a thickness of 10 mm and contained ribs of different widths (1-10 mm), each 3 mm high, on both sides, arranged in the flow direction. The total thickness of the specimen was thus 16 mm for the ribs. For the first 360 s after ignition with a Kanthal wire, the flow velocity was 20 cm/s in the opposed direction. Then the flow velocity was reduced to 5 cm/s for a duration of 300 s before it was switched off to terminate the experiment. The experimental pressure was 761 hPa and the oxygen concentration was 26.9 vol %. These conditions correspond to atmospheric conditions envisioned for future exploration missions. It was found that the flames ignited downstream propagated forward along the rib edges surprisingly fast with up to 0.88 mm/s (1 mm rib width). Also, it was observed that the wider the rib, the slower the propagation. The widest rib (10 mm) already showed two largely independent edge flames. Unintentionally, the experiment showed how sensitive the flames are to small perturbations of the flow field, as remnants of a preceding and upstream experiment disturbed the incoming flow stratification partially.

I. Introduction

Our expectations of the combustion of solid materials under 1g conditions are accustomed to their complexity even if we do not always understand the details underlying this process. In this respect, the combustion process under microgravity conditions may hold surprises, although the same laws apply there as on the ground. The results

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of a combustion test on the CYGNUS re-supply spacecraft in the context of the SAFFIRE V experiment discussed here show this impressively. While under 1g conditions a fire spreads preferentially upward with the convective flow and hardly against it downward, it is exactly the opposite in microgravity and forced flow even if the velocities of the spread differ. But the lower propagation velocities and burn rates in microgravity do not equate to reduced hazards, since much larger amounts of flammable flue gases are produced than on the ground. In matters of fire safety of an orbital habitat, it is therefore particularly important to understand the basic processes and their effects, and to derive standards from them that will, on the one hand, largely reduce the risk of fire occurrence and, on the other hand, allow reasonable strategies to minimize the spread of fire and its consequences. Current standards for material selection provide for 1g fire tests on upright flat specimens¹⁻³. Of course, these conditions are different in a spacecraft - both in terms of gravitational conditions and material shape.

If a sample of PMMA is ignited under 1g conditions, then large temperature gradients in conjunction with buoyancy convection ensure the emergence of strong velocity gradients in both upward and downward combustion. This leads to a local stretching of the flow field and consequently to the formation of vortices due to shear instabilities. This results in the well-known flickering of a flame, which is caused by the ingression of air with directional components normal to the direction of the buoyant flow. Figure 1 schematically shows the scenario of an upwardly directed combustion.

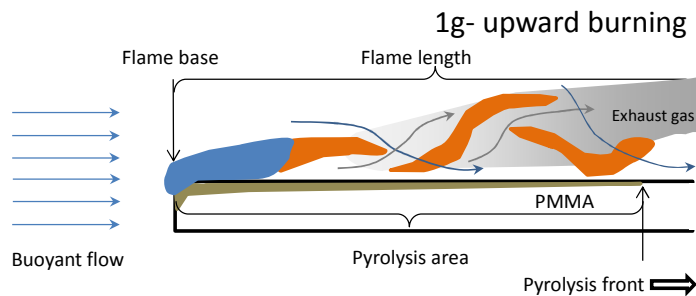


Figure 1. Terminology and basic phenomena in upward combustion under 1g conditions.

Due to this mixing of air not only from below (in Figure 1 from left), there is always sufficient oxidant available for the pyrolysis gas. This leads to a blazing flame and to the fact that flame length and pyrolysis area grow steadily and the pyrolysis area spreads rapidly upwards over the surface of the sample. The air mixing also means that the combustion of the excess pyrolyzate can take place almost completely, at least in the case of the PMMA investigated here, so that hardly any soot or unburned MMA are produced. The main gases leaving the

reaction zone at the top (to right in Figure 1) are CO₂ and water.

This is probably the most important difference in its effect to a corresponding fire scenario under microgravity and forced flow. In microgravity, however, the flow field remains stratified through the reaction zone in laminar flow despite thermal expansion and local density gradients due to the lack of weight differences. As a result, atmospheric oxygen can only reach the flame from upstream. This case, which is simpler in principle, has surprisingly far-reaching consequences. Figure 2 shows schematically the phenomena of μ g combustion under forced concurrent flow conditions.

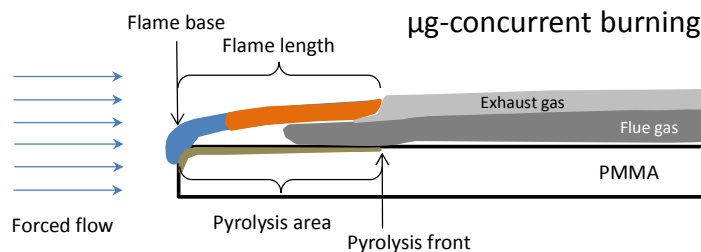


Figure 2. Terminology and basic phenomena in concurrent combustion under microgravity.

By maintaining the stratification, only the flame base is sufficiently supplied with oxygen. The stationary flame length is as limited as its burning rate⁴. Under the flame, the material is heated up to the pyrolysis temperature, but pyrolyzate is protected by the flame against the entry of atmospheric oxygen and carried away with the flow. In addition to the exhaust gas, a considerable amount of potentially combustible flue gas is thus also produced. Since only the flame base is

well oxygenated, there is no possibility for the burning zone to propagate across the material surface. Instead, the pyrolysis front propagates to a length where the radiant power of the flame is insufficient to reach the pyrolysis temperature. The flame base propagates at the rate at which the material is completely consumed at the leading edge. For given atmospheric conditions, the propagation speed of the flame base therefore depends mainly on the thickness of the material. The propagation of the burning zone with the flow, which is self-evident on Earth, is therefore rather unlikely in microgravity. If one increases the inflow velocity, from a certain flow velocity on, the

flame lifts off, jumps repeatedly back to its base before it extinguishes. So there might be a very small and sensitive velocity range in which a lifted flame is very slowly driven over the preheated surface, but not yet blown out. But this has not been observed during blowoff-tests on burning rod tips in microgravity⁴ where this burning regime was unstable marking the transition to blow-off.

Flame propagation against the incident flow occurs on Earth very slowly compared to its spread rate in concurrent flow. As this propagation happens in the flow boundary layer with decreasing velocity towards the wall it is the faster, the lower the pressure and the thicker the related boundary layer is⁵. Any additional forced flow leads to an increase of the local burning rate, but also reduces the velocity of the flame base against the incident flow. This is different in microgravity: even at low flow velocities, the flame base propagates rapidly against the flow. The faster the incoming flow becomes, the more oxygen reaches the base and the faster the flame propagates against it. Figure 3 schematically shows the corresponding scenario.

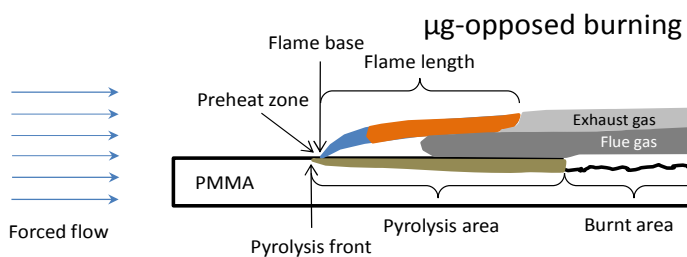


Figure 3. Terminology and basic phenomena in opposed flow combustion under microgravity.

flow velocity and flame propagation velocity reach equilibrium and where the flame base becomes stationary and works its way into the depth of the material. This marks the limit towards blowoff.

What has been described applies to thick materials, as studied in SAFFIRE V, which cannot be assumed to be isothermal to depth. If the materials are very thin, flame base and burnout end coincide. Then the phenomena of concurrent and opposed combustion are comparable⁶. However, spread rate and its dependence on flow and pressure remain different. What actually propagates is the material edge and with it inevitably the flame base.

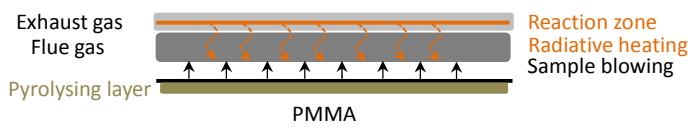


Figure 4. Schematic section through the layers above a burning flat sample under microgravity.

the burning specimen. In the current qualification standards, however, the edges should also be protected against burning. As is typical for a diffusion flame, the combustible exhaust gases are produced on the fuel-rich side of the reaction zone. It becomes clear that, with a flow into the image plane, after a certain run length diffusion of oxidant perpendicular to the flow can no longer play a significant role in mass transport.

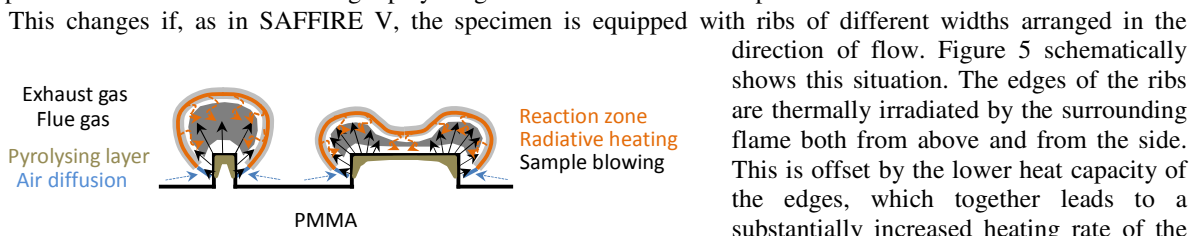


Figure 5. Schematic representation of flames over ribs arranged in the direction of flow under microgravity.

material thus also corresponds to the shape of a thermal isoline. If the rib is narrow, the edges interfere and a largely

The most active combustion zone is the flame base that is best supplied with oxygen. Consequently, it propagates preferentially in the direction of fresh air. As with concurrent combustion, the flame length is finite and it produces a lot of unburned flue gas underneath. Downstream of the zone with sufficient pyrolysis temperature, the flame leaves a zone with burnt surface. Analogous to concurrent combustion, there must be an upper limit to the inflow velocity at which

The case studied in SAFFIRE V includes another important aspect caused by the material shape. Figure 4 shows the situation initially for a flat specimen not in a lateral but in a frontal section. The shown stable stratified situation changes towards the not shown edges. In this respect, this is the situation in the center of the burning specimen. In the current qualification standards, however, the edges should also be protected against burning. As is typical for a diffusion flame, the combustible exhaust gases are produced on the fuel-rich side of the reaction zone. It becomes clear that, with a flow into the image plane, after a certain run length diffusion of oxidant perpendicular to the flow can no longer play a significant role in mass transport. This changes if, as in SAFFIRE V, the specimen is equipped with ribs of different widths arranged in the direction of flow. Figure 5 schematically shows this situation. The edges of the ribs are thermally irradiated by the surrounding flame both from above and from the side. This is offset by the lower heat capacity of the edges, which together leads to a substantially increased heating rate of the edges. As a result, the edges burn preferentially, and the flame base advances along the edges. The qualitatively depicted shape of the pyrolyzing layer in the

closed flame forms around both edges, reinforcing each other. If the rib is wide, the interaction between the edges decreases and two edge flames are observed. Again, as long as the two edges are not far enough apart to be two single step flames, the base of the flame will propagate faster than with a single step. If adjacent ribs are not far enough apart, then they too accelerate propagation via radiative exchange. In this case, the propagation of the flame base is so fast that, if the ribs are not far enough apart, there is insufficient heating between them and the valleys consequently do not burn. This probably leads to a further effect accelerating the propagation speed, which consists in the fact that at the flame base oxygen can also reach the reaction zone from the valleys and over a short diffusion length, i.e. with a component normal to the flow direction. Since the thickness of the laminar flow boundary layer is pressure-dependent, this effect should also be pressure-dependent if the geometry is constant.

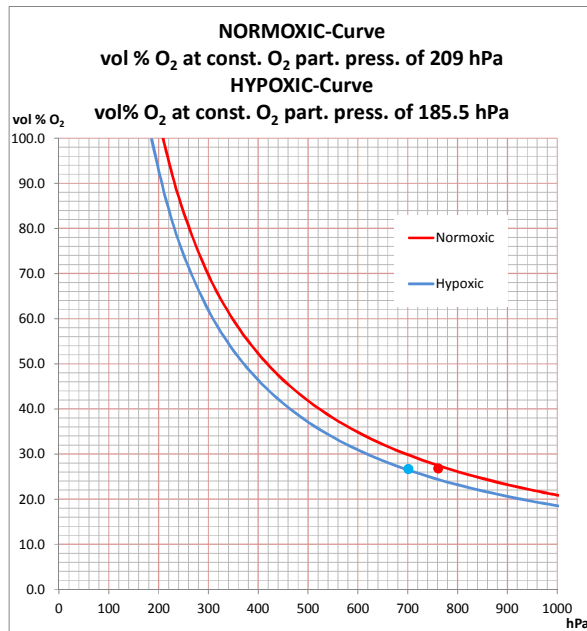


Figure 6. Atmospheric condition at the start of the experiment (red dot) relative to the NORMOXIC and HYPOXIC curves and the conditions currently envisioned for future exploration missions (blue dot).

II. Experimental Setup

The SAFFIRE V experiment consists in its core of a rectangular wind tunnel with a height of 305 mm, a width of 460 mm and a length of 1100 mm. This has remained basically the same through all SAFFIRE campaigns^{7,8}. The apparatus has been improved in many details and equipped with additional sensors, which also investigate the effect of the large-scale combustion experiments on the atmosphere of the spacecraft. The apparatus inhales the surrounding atmosphere of the spacecraft, accelerates and laminarizes it to the desired flow velocity, and returns it to the atmosphere of the spacecraft at the exit of the wind tunnel. For the experiment described here, the atmospheric pressure inside CYGNUS was lowered to 761 hPa and the oxygen content was increased to 26.9 vol% by enrichment. Figure 6 shows that these conditions on the HYPOXIC curve are close to the point of future planned exploration missions (700 hPa/ 26.5 vol% O₂).

The specimen studied is shown in Figure 7. It consists of cast PMMA of 10 mm thickness, on which ribs of widths 1–10 mm are attached on both sides in the direction of flow. The distance

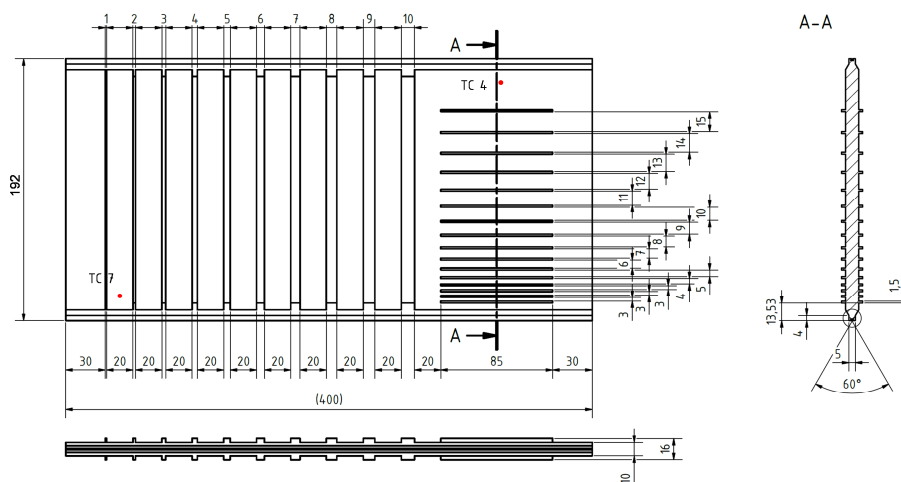


Figure 7. Geometry of the both-sides burning specimen made of PMMA cast and provided with surface structures. The red dots indicate the position of two thermocouples TC4 and TC7. All dimensions in mm.

between the ribs is 20 mm.

The determination of these distances as largely interaction-free was based on the results of SAFFIRE II test⁹, in which a specimen with a central groove was examined. Next to this, horizontal ribs, each 1.5 mm wide and with rib spacing increasing in the direction of flow, are placed transversely to the direction of flow. All ribs are 3 mm high. The distance

between the structures and the edge of the specimen is 30 mm on both sides. The specimen is provided with a resistance heating wire at both ends for ignition. To facilitate ignition, the specimen is tapered towards the ignition ends over a length of 4 mm to a thickness of 5 mm. This is followed by a ramp which reaches the height of the upper edge of the structures after a length of 13.53 mm. It was planned to ignite the Figure 7 sample first at the upstream end (concurrent) and to ignite it again at the downstream end (opposed) in a later experiment. The ignition of the first experiment failed because the igniter had apparently lost its electrical contact. In this respect, the experiment was limited to the trial in opposed flow configuration. In this respect, the horizontal ribs, on which it was to be tested in concurrent configuration whether and how the flame jumps from rib to rib, play no role here. As will be shown later, however, it turned out to be an advantage that the sample had not yet been burned by the upstream end. The experimental module was equipped with three samples, mounted in one plane at half channel height, which were processed one after the other. The sample treated here was sandwiched between an upstream cotton sample 400 mm wide and 500 mm long and a flat PMMA sample 5 mm thick, 400 mm wide and 200 mm long. The other two samples were processed prior to the experiment described here.

Figure 8 shows the conditions at the beginning of the test. It can be clearly seen that the cotton sample did not burn without residues, and that the residues therefore represented an obstacle which influenced the flow of the structured PMMA sample, as shown later.

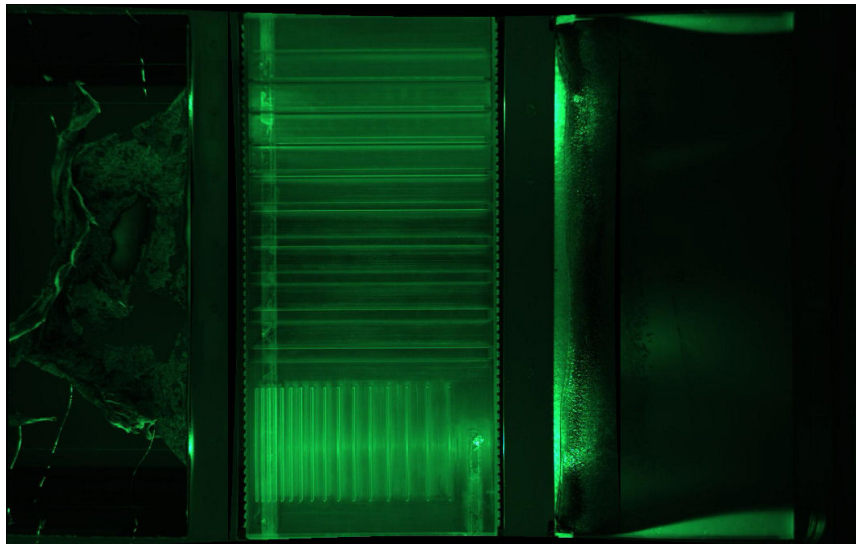


Figure 8. Left: Remains of the cotton sample, Middle: Sample before ignition started, Right: Remains of the 5 mm PMMA sample. Incident flow from left.

The experiment first starts with a 10 min phase during which the resistance heating wire is energized with a power of 2.5 W for 10 min. This heats the ignition region of the sample, and facilitates the subsequent ignition with 30 W for one minute. This takes into account the experience with previous experiments with thick PMMA samples that this minimizes the risk of burning through the heating wire during the otherwise longer ignition phase and also makes it easier to pyrolyze the ignition area, reducing the risk of extinction after the ignition

power is switched off. The flow is ramped up to 20 cm/s and once stationary, the preheating and subsequent ignition sequence is started. After the heating power is increased to the ignition power the flow condition of 20 cm/s is maintained for 360 s before the velocity is reduced to 5 cm/s for another 300 s. This second firing period at reduced flow is also inserted for safety reasons to cool the sample down at reduced power before the flow is shut off. This is to prevent hot pyrolysis gas from accumulating and possibly igniting. However, this long burn time at reduced speed incidentally provides a second experimental condition.

During the experiment, the progress of combustion is recorded frontally (as in Figure 8) at a frequency of 30 fps and from the side at the same frequency in the visible spectral range. A green LED light is used to expose the sample with a frequency of 0.5 Hz for three frames (0.1 s).

III. Results and Discussion

Before the evaluation, all images were first distortion corrected and the images taken with automatic camera gain were normalized to the brightness value of the darkest images during 5 cm/s.

The first indication that the incident flow is not perfectly stratified everywhere is provided by the moment of ignition. This occurs in a deflagration, which is typical for the ignition of a premixture gradually developing during the warm-up period and which was also observed during earlier experiments, but here it is much more violent than normal. The Figure 9 shows successive images of the moment of ignition. The ignition point from which the flame spreads across the entire width of the sample can also be seen. The rather strong deflagration is probably due to the fact that the slightly disturbed inflow led to a partial mixing and dilution of the pyrolysis gases. This leads to delayed ignition until a sufficient concentration of OH radicals has accumulated with subsequent thermal runaway, and a larger quantity of premixed combustible fuel-air mixture has accumulated.

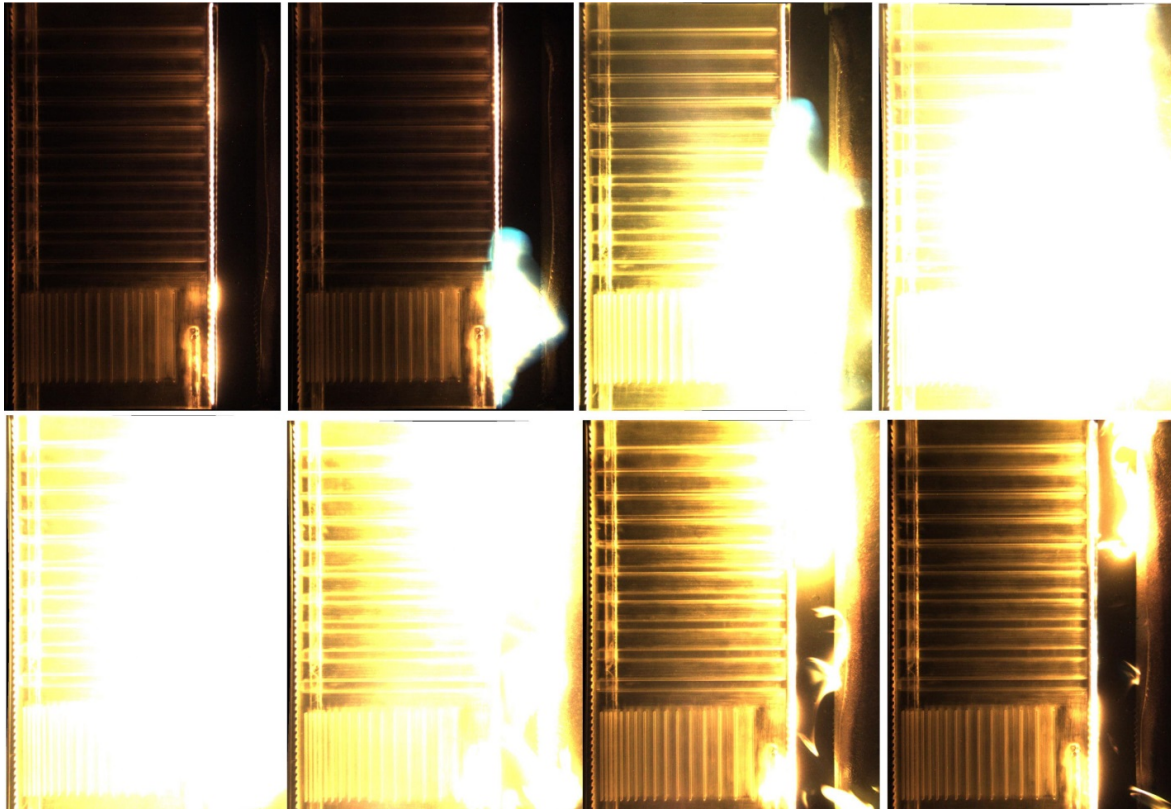


Figure 9. Deflagration type of ignition. Recording interval 33 ms.

Figure 10 shows two snapshots during the steady flow of 20 cm/s (after 260 s) and during the steady flow of 5 cm/s (after 600 s). It can be clearly seen how the flame base propagates along the ribs. The propagation speed is impressive, as is the precision with which propagation speed and rib width are correlated. In the following, the ribs are labeled 1 to 10 according to their width in mm from top to bottom in Figure 10. At first glance, it can be seen that either rib 7 lags a little, or ribs 8-10 lead a little. This will become clearer in the following quantitative evaluation. The cause for this is also suspected to be an inflow that does not remain perfectly stratified and fires up the flames due to the associated mixing in of additional oxidizer. It can also be seen immediately that already the flame front of rib 2 shows a rectangular profile, corresponding to two closely spaced propagation fronts along the two edges. As the rib width increases, the two fronts become more distinct and different velocities become visible. Nevertheless, the two edge flames influence each other because the difference in front positions along a rib remains limited. These differences balance out with decreasing firing rate at 5 cm/s. Here, obviously, the individual edge flame loses strength and the range of interaction increases accordingly. Both during 20 cm/s and during 5 cm/s, two flame fronts can be recognized in the case of ribs 8-10. During the progressive combustion, a total of 4 flames become visible on these ribs. It is assumed that the trailing flame front is the shining through of the rear-side flame, which progresses at slightly different velocities. Front and rear side can be distinguished by intensity and sharpness. In this case, the flame bases most ahead are located on the front side of the specimen. The fact that the difference is only visible at ribs 8-10 also speaks for slightly different flow conditions on the front and back side here.

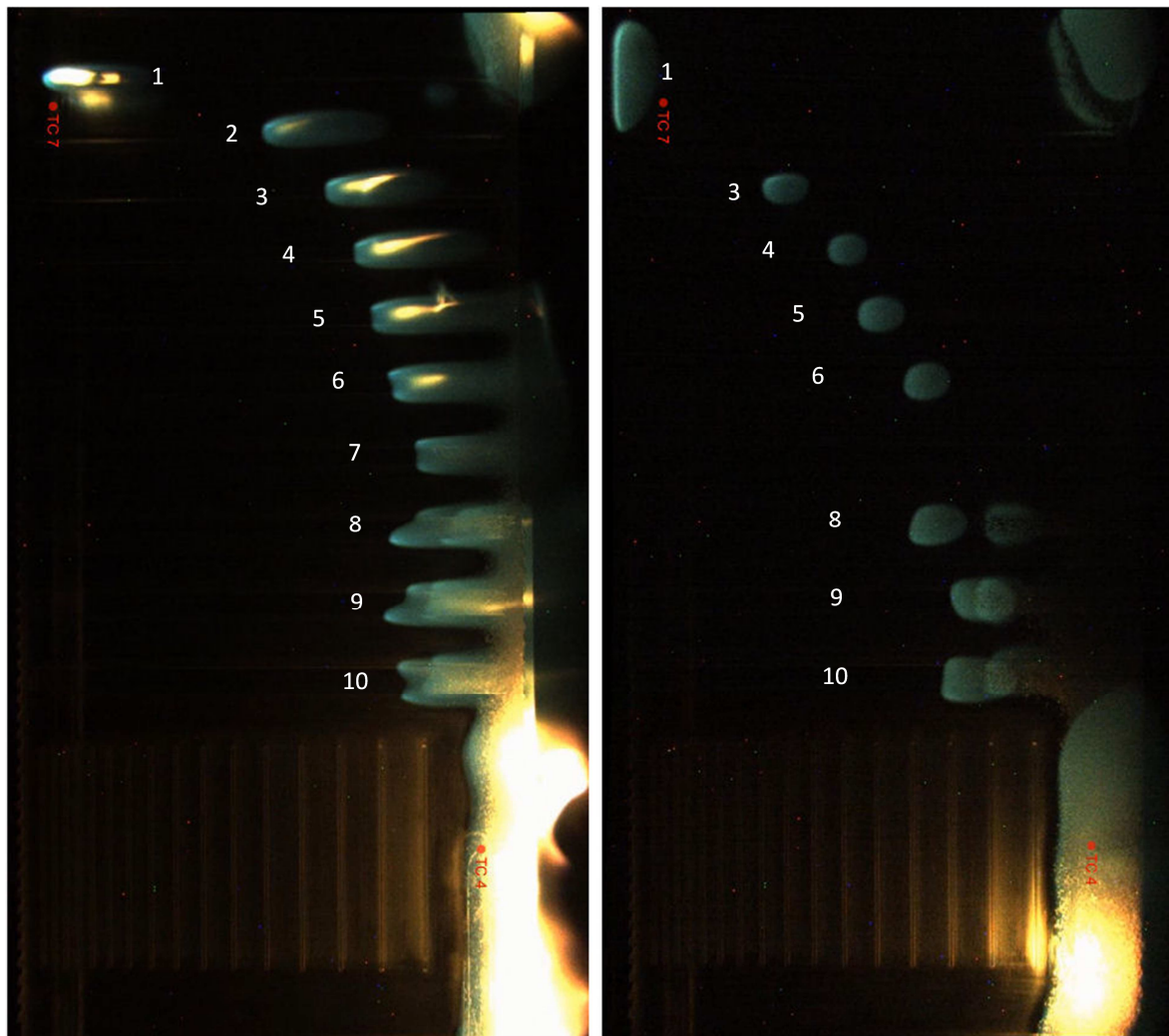


Figure 10. Steady-state firing progress: left after 260 s (20 cm/s), right after 600 s (5 cm/s). Incoming flow from the left.

One can notice that the flames, after they have detached from the trailing edge, have a limited length. This means that the shadowing effect¹⁰ through the flame prevents oxygen from reaching downstream regions. As described in the introduction, this results in a finite flame length in contrast to 1g conditions. The fact that the areas behind the flame are extinguished, although there must still be fuel raised above the base surface, means conversely that a flame cannot move in the opposite direction downstream as the flame isolates the fuel downstream against oxygen as long as the flame base has not consumed the fuel totally at the leading edge and moves downstream with the burnout end. This shadowing effect is also evident in rib 2. After 290 s, during the 20 cm/s burning period, the flame of rib 1 reaches the leading edge of the specimen. Once there, it gradually spread out in width along the leading edge. After 567 s, i.e. already during the 5 cm/s burning period, it has spread in front of flame 2. At this point, flame 2 is still 28 mm apart from the leading edge and extinguishes in the shadow of the flame in front of it. In Figure 10 on the right, the flame of rib 2 has already gone out.

Not only does rib 7 lag behind, it also shows the edge flames with the lowest luminosity throughout the experiment. During the flow is ramping down to 5 cm/s, the flames of rib 7 extinguish after 10 s. This is associated with an unfavorable incident flow, as will be shown later.

Figure 11 shows the results of CFD simulations on the influence of the structures of the specimen on the flow field in a non-reacting situation. At the test pressure of 761 hPa, the laminar flow boundary layer reaches a thickness of almost 50 mm. As a result, in the top picture, one can see an influence of the flow by the specimen as a whole, but

hardly any influence of the structures, which protrude only 3 mm above the specimen. If one zooms in a little closer to the horizontal ribs, one sees local disturbances, but their values are very small and have very little influence on the flow field shown in color. It can be seen, however, that the flame in the shallow area, downstream of the horizontal ribs, can have a problem when it approaches the deadwater area behind the last rib. This location was reached by the end of the test. Not shown, however, is the effect of the flame. The thermal expansion associated with it forms a much larger object that affects the flow field more than the ribs.

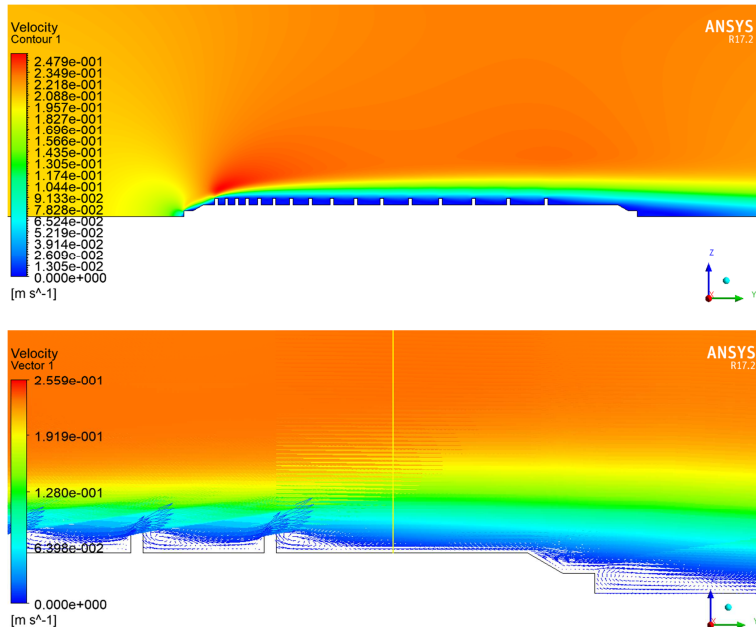


Figure 11. CFD simulations of how the cold flow field is influenced by the sample structure. Cross-section at the center of the horizontal ribs.

stretched in the side view, it is swirled horizontally in the top view. The flow is relatively little disturbed in the area of ribs 1-4 and above the horizontal ribs. This should be taken into account in the quantitative evaluation. The

In this respect, the effect of the cotton residues upstream of the structured sample which were not simulated as its geometry is not known enough must be taken into account. Figure 12 shows a visualization of the flow field by smoke filaments generated at a height of approx. 50 mm above the sample, before and after the tests.

First, on the left, one can see the uniformity of the flow field and the good agreement with the simulation in Figure 11, and on the right, one can see the disturbances caused by the cotton residues. In particular, the region around ribs 6-8 is bypassed by the streamlines, while the streamlines in the region of ribs 9 and 10 are compressed and swirled. In particular, the streamline in the region of rib 9 is pressed downward, tightly over the specimen, during the entire recording time. While it remains

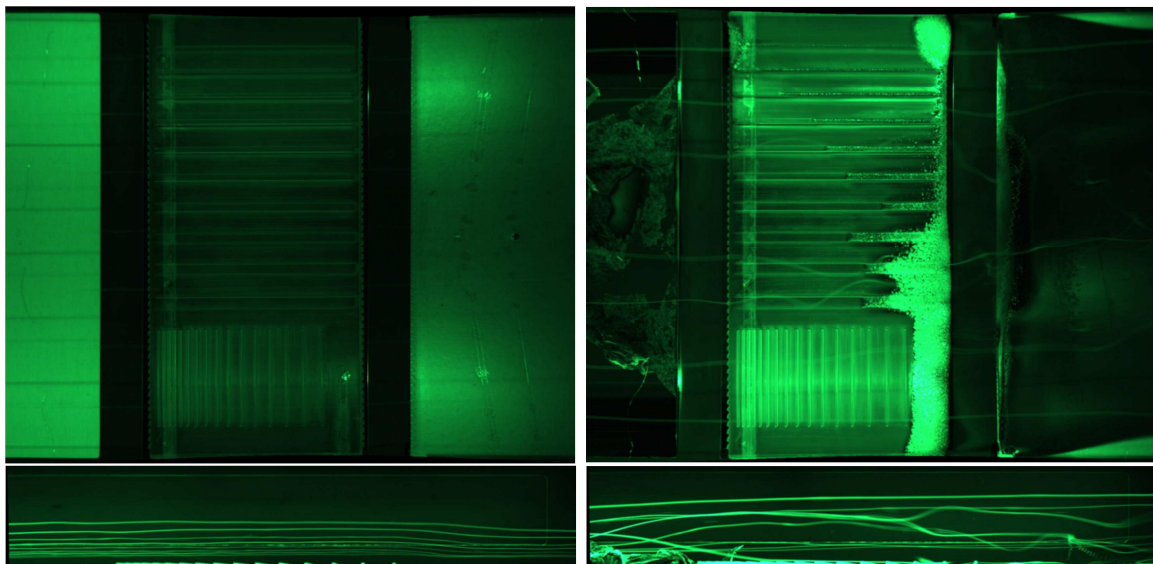


Figure 12. Flow visualization before (left) and after (right) the experiments. The flow disturbing residues of the cotton sample are as well visible as it's effect on the total propagation at the trailing edge.

position of the pyrolysis front along the various structures is also very well discernible, showing that only in the interstices of ribs 8-10 and towards the edges of the sample has there been any appreciable propagation. This can be easily explained by the downwardly pressed and horizontally swirled incident flow and, towards the edges, by the denser adjacent flow as well as the protruding outer specimen edges. The fact that there was no even stronger propagation along the edges is again due to heat losses in the aluminum mask holding the specimen, which engages in a groove on the outside and has a distance of only 4 mm from the specimen edge. This effect was already observed with the similarly held samples of the SAFFIRE II experiment⁹.

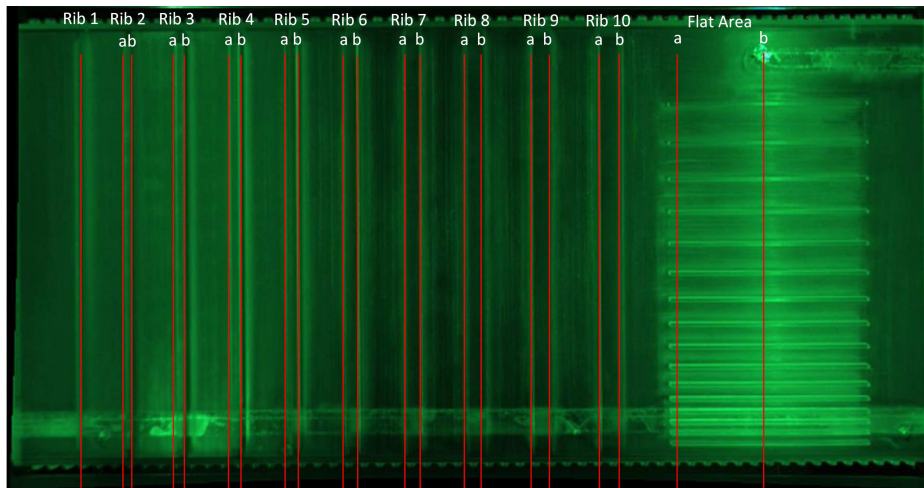


Figure 13. Lines and their designation along which the evaluation was performed.

constant the propagation velocities at 20 cm/s and 5 cm/s become after a start-up and transition time, respectively. Only the flames 2ab deviate from this during 5 cm/s, since they are gradually shadowed by the flame of rib 1 until they are extinguished after 567 s, and the flames 9ab also deviate during 5 cm/s. The reason for this must be a change in the incident flow with the velocity change, since flames 9ab were still in front of ribs 8 and 10 during 20 cm/s, but fall behind them with the slower incident flow (Figure 10). The velocities averaged over the fronts a and b are shown in Figure 15.

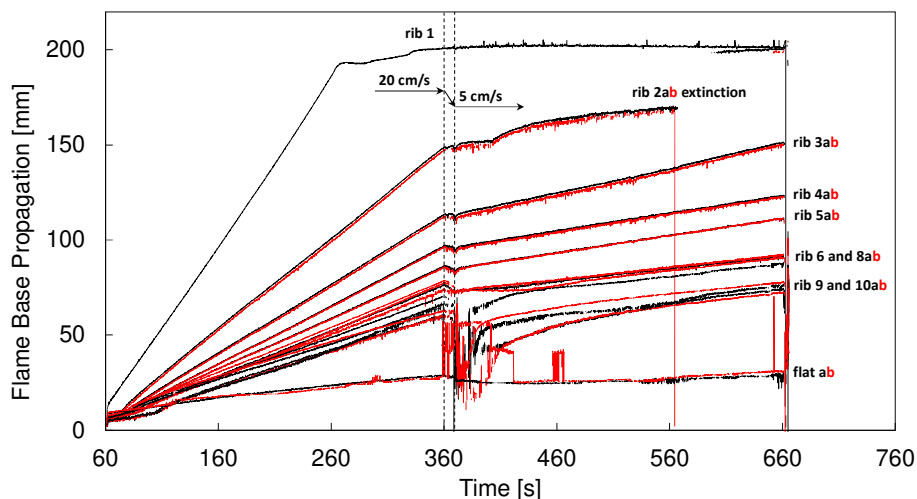


Figure 14. Propagation of the flame base along all evaluation lines. Time from start of ignition.

ribs 1-6 and extrapolated to rib 10. It can be seen that the correlation improves and that the deviations are more evident with ribs 8-10. The high propagation speed along the edge is determined by the higher heating rate there.

For the quantitative evaluation, Figure 13 first shows the lines and their names along which an automatic evaluation was performed. Figure 14 shows the propagation fronts over time. For this purpose, the first time a brightness threshold was exceeded was defined as the flame base along the evaluation lines, looking from bottom to top. It can be seen how amazingly

As can be seen in Figure 15, the propagation velocities follow an inverse potential relationship (blue). Rib 7 is behind the trend while ribs 8-10 are ahead of the trend. Therefore (in red) the trend line is determined only with

Here, the surface over which radiation is absorbed plays a role, as well as the heated volume into which the heat is conducted. According to Delzeit et al.¹¹, the internal edge angle determines the propagation velocity. However, since this is the same for all ribs, the mutual amplification of the two edge flames, which decreases with increasing rib

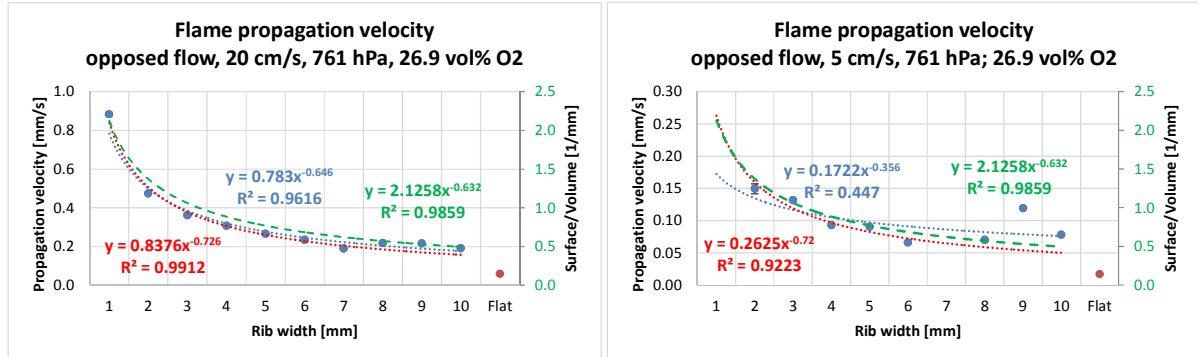


Figure 15. Propagation speed of the flame base at 20 cm/s and 5 cm/s. Blue: experiments and its trend, red: trendline calculated with ribs 1 through 6 only, green: rib's surface/volume ratio.

width, must cause the different propagation rate. Thus, the heating rate is initially determined by the surface/volume ratio. In the 2-D representation, the radiation absorbing surface area becomes the contour length via the cross-section, and the rib volume becomes the cross-sectional area of the rib. If one divides the contour length ($2 \times$ rib height + rib width) by the rib cross-sectional area and applies this over the ribs, one obtains a potential curve, which is additionally entered in Figure 15 as a dashed green line and makes the relationship seem obvious. In fact, the wider ribs should not follow this curve exactly, because here there are no longer completely closed edge flames, but two edge flames and a flat-area flame in between, whose effects overlap. Thus, the wider the rib becomes, the more should the propagation velocity be below this trend. There is another interaction which determines the heating rate, and which is not taken into account in the heating rate defined above: if the rib's elevation above the base plate is low, then the angle between the base plate and the rib (to be referred to as the exterior angle according to Delzeit et al.¹¹) must have a cooling effect via the heat receiving surface area which is increased here compared to the heat emitting flame. In this respect, the height of the ribs, and not only their widths, also plays an influencing role. Since the heights were not varied here, its quantities remain open. Regardless of whether the wider ribs are two independent edge flames or two mutually amplifying edge flames, they must in any case always propagate faster than the flames of the flat area, and extrapolation of the trend lines into the flat area is not permissible. This becomes particularly clear when the inflow velocity is reduced by 75%. For all flames, the propagation velocity is reduced by a comparable percentage of about 75%, consistent with the thermal theory of de Ris¹² for thick fuels that predicts flame spread rate varies linearly with the flow velocity. This can vice versa be taken as an indication that reducing or switching off the air circulation, if operationally possible, can be a very suitable fire-fighting measure.

The determination of the flame lengths is shown in Figure 16. The evaluation was carried out by the additional determination of a point along the lines at which a brightness threshold value was undershot. The flame length here

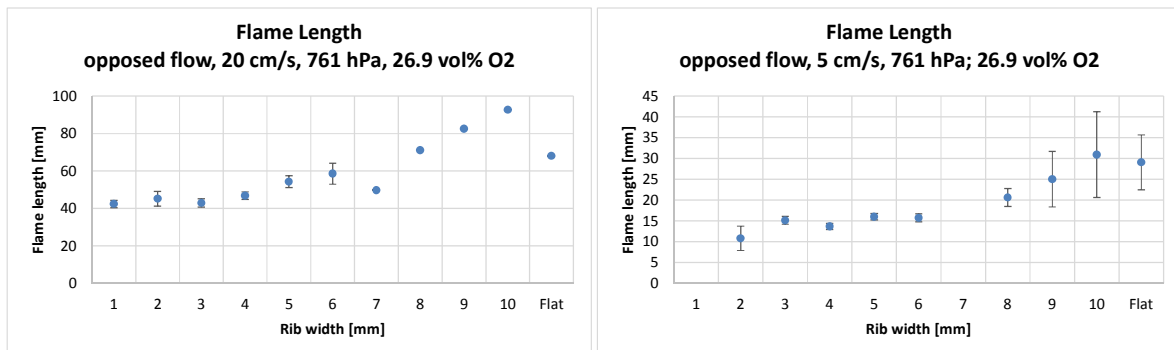


Figure 16. Flame lengths at 20 cm/s and 5 cm/s.

refers to the brightness of the normalized image values and is used for comparison. It is therefore not to be equated with the chemical length of the reaction zone, e.g. by measuring the OH concentration, due to the lack of diagnostics.

If one also assumes here an influence by different inflow conditions in the area of ribs 7-10, then the values of the remaining ribs speak for a comparable finite flame length. Thus, although one rib region is preheated by the flame passing over it, this region does not continue to burn and does not result in a flame that increases in length with time. Again, this is a clear indication that propagation may preferably, if not exclusively, be opposed. The flame lengths of ribs 7-10 are overestimated because for all rib flames a reliable measurement of length is possible only after the flames have separated from the trailing edge, i.e., after there is a non-burning sample region behind the flame. This condition was not reached for ribs 7-10 because of too short test time and/or because of swirled inflow. In this respect, the end of the flame remained "pinned" to the trailing edge of the specimen. For ribs 7-10 the length of this pinned flame at the end of each flow condition is displayed in Figure 16. Therefore no error bar is given. This pinned flame situation changed after the transition to 5 cm/s. During the transition, flames 8-10 began to extinguish for 40 s and were repeatedly reignited from the trailing edge. In particular, rib 9 exhibited this striking behavior which is indicated the large error bars in right part of Figure 16. After 40 s, this behavior came to rest and the flames of ribs 8-10 were now off the sample trailing edge. It is remarkable that all ribs now show a single closed blue flame, so that no individual edge flames can be detected. With a weak inflow and thus reduced flame power, the difference between edge behavior and surface behavior seems to balance out.

In order to get a better picture of the possible effect of the inflow perturbations, intensity fluctuations of the flames are evaluated. The assumption is that the more turbulent and thus the more unsteady the incident flow, the stronger the intensity fluctuations of the flames should be. For this purpose, an evaluation range is first defined for each rib, which spans the length of the flame vertically and is defined horizontally for each rib in such a way that the luminous region is completely contained. Figure 17 shows the standard deviation of the brightness of this area from the mean value over the entire test period. The unit is the brightness value as deviation from the mean value and can take values between 0 and 255.

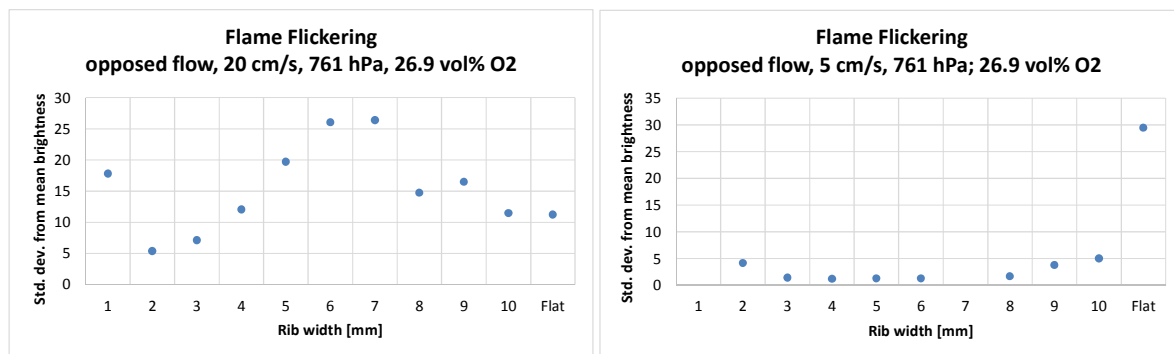


Figure 17. Standard deviation from mean flame brightness for 20 cm/s and 5 cm/s.

Here, large deviations become apparent, especially at 20 cm/s. The deviations from the mean brightness value reflect the displacement and vorticity of the incident flow from Figure 12 on the right very well. Only rib 1 shows intensity fluctuations, which were not to be expected from Figure 12. However, the snapshot of Figure 10 already shows that rib 1 carries a conspicuous flame. It can be assumed that Figure 17 represents a very good image of the inflow conditions and that, on the basis of this, a good classification of the quantitative values can be made. The flames calm down at 5 cm/s and their intensity variations become very similar. Here, the flat area stands out, which is due to the strongly flickering flame of the back side, which shines through to the result of the front side. However, when looking at all the images of the recorded video, it can be assumed as certain that the position of the TC 4 thermocouple, which lies on the evaluation line of the flat area b, shows idiosyncratic combustion processes, which are to be associated with the installation and bonding of the thermocouple.

IV. Conclusion

To investigate the effect of structures on opposed flame propagation, a PMMA specimen of 10 mm basic thickness with vertical ribs of identical height above the basis (3 mm) and different widths (1 -10 mm) was ignited at the downstream end during SAFFIRE V.

It could be shown that flames propagate very fast along exposed edges in opposed flow. This propagation depends on the heating rate and is therefore faster the closer the edges are to each other. The propagation velocity follows an inverse power relationship, which is based on the heating rate determined by the surface/volume ratio.

In comparison to SAFFIRE II, where two edges of a wide groove were investigated in concurrent flow, it could be shown that flames propagate with the flow along edges or over a surface only in exceptional cases. This is particularly evident from the fact that the flames in this opposed flow experiments assume a finite and largely stationary length and do not span a burning surface during propagation.

In both opposed and concurrent flow, the amount of potentially combustible flue gas formed under the flame increases with time which correlates with the increasing heated and pyrolyzing area underneath the flame.

The velocity of propagation is largely proportional to the inflow velocity, consistent with thermal theory of de Ris¹².

Even very small disturbances of the stratification can clearly demonstrably favor combustion. Since any active firefighting measure also forces a disturbance of the stable stratification, it is obvious to alternatively consider a shutdown of the air circulation as the primary control measure. This conclusion is strengthened primarily by the fact that the experimental conditions studied here are idealized conditions of inflow with as little vorticity as possible. In the real scenario, where the flow is affected by corners, edges, and cross-section changes, as well as by human activity, flow calming must be particularly effective. One lesson to be learned from the previous SAFFIRE IV experiment, where a deflagration destroyed the apparatus after the cutoff flow was restarted after a short period, is that actively cooling the still burning material by reducing the flow rather than completely shutting it down may be a better way to avoid flashover effects.

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