Final report

of the

OTKA-FK 124704 grant

(01/09/2017–30/11/2021)

Publication summary

- 1 authored book at Springer
- 16 IF papers (WoS: 10 Q1, 2 Q2, 3 Q3, 1 Q4), 14 included the grant in the acknowledgment (8 Q1 out of 10 Q1 papers and all the other papers)
- 1 Hungarian patent application, PCT in progress (patents do not have acknowledgments section)
- 7 journal papers without IF: 2 English at international publishers (1 included the grant in the acknowledgment), 5 Hungarian
- 16 conference papers: 9 International, 7 Hungarian
- 1 preprint at arXiv, it was invited to Physics of Fluids (WoS Q1)
- 1 invited and submitted paper to the Fuel journal (WoS Q1)
- 4 more manuscripts will be submitted next year to WoS Q1 journals from the acquired measurement data

Completion of the research plan

Fortunately, all the tasks of the research plan were properly addressed and completed in the four-year time, even though we had to rearrange our tasks if one thread was hindered. More details on the progress can be found in the yearly reports. The five numbered sections below detail the highlighted results of the research project. Performed extra tasks:

- Design & construction of an ammonia line, allowing NH_3 combustion.
- Extensive measurement of liquid fuel combustion by Schlieren and Phase Doppler Anemometry (PDA) in the summer of 2021. The high-speed camera, the laser system, and the 3D traverse were all brought by Dr. Milan Malý, a guest researcher from Brno.
- Extensive investigation of selected thermophysical properties of various renewable, fossil, and blended fuels.
- Fundamental advancements in liquid fuel atomization, droplet evaporation, and numerical modeling of distributed combustion.
- Active collaboration with the Brno University of Technology, Czech Republic and the Shanghai Jiao Tong University, China.
- Establishment of the BME Combustion Research Group (https://crg.energia.bme.hu/).

Research personnel

The current grant started with Dr. Krisztián Sztankó and Attila Kun-Balog as researchers. However, along with the expansion of the research group, the tasks were shared with five additional talented students who started PhD studies under my supervision over the years. We had a guest researcher from Brno University of Technology and two interns from Orleans, France, who spent one semester at BME, all three during the summer of 2021.

1. Design, construction, and operation of the new test rig

The new combustion test rig was built in the first two years of this grant, see Figs. 1 and 2 for details. Meanwhile, the old test rig was still used for measurements, and the focus was on fundamental topics. The construction was notably delayed principally by the slow administrative processes and some supplier delays. The key design guidelines for modern combustion chambers were published in a book [1]. However, the amendment of the test rig was continued in the last two years, but to a smaller extent to make the measurements easier or add other functions to the system. The most notable upgrade was performed in 2021 with the addition of the ammonia line and the corresponding instrumentation. Also, we started preparing for Particle Image Velocimetry measurements, therefore, a new combustion chamber was designed and manufactured.

Fig. 1. 3D CAD drawing of the test rig (left) and the assembled system (right).

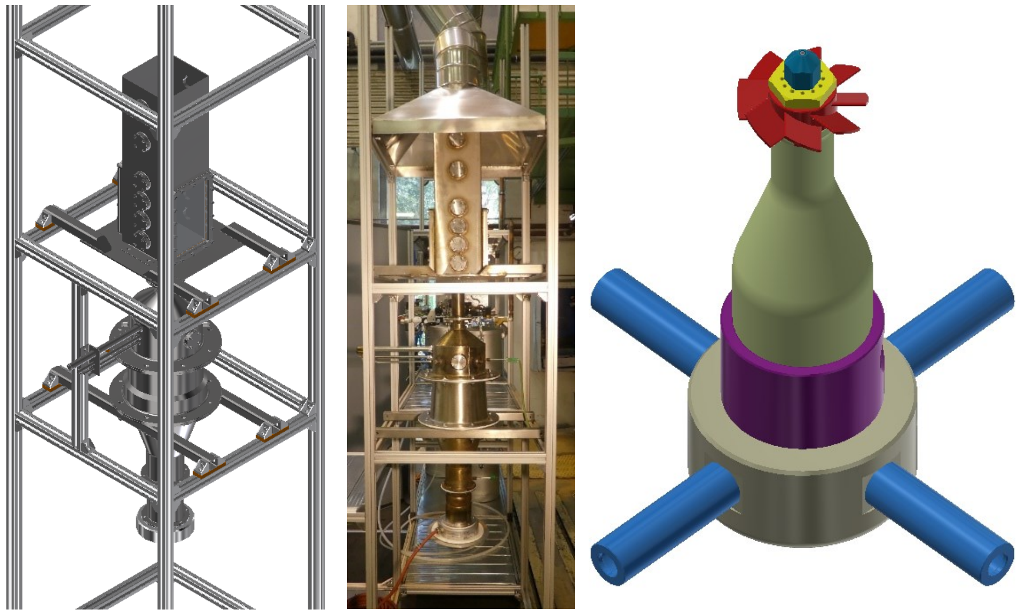

Fig. 2. The combustion system on CAD (left), in reality (middle), and the CAD drawing of the dual-fuel burner (right).

Since the budget was highly limited, we have designed all the electric, control, and data acquisition systems. Obviously, we asked a professional electric engineer to check our wiring and instrumentation concept and the leading electrician of the university to check the system before turning the power on.

2. Distributed combustion

The criteria of achieving distributed combustion are well-known in the literature: lean fuel-air mixture and low-oxygen dilution [2]. However, we managed to establish distributed combustion without combustion air dilution [3,4], which is the most significant result of this grant. The novel concept was named Mixture Temperature-Controlled (MTC) combustion. See sample flame images in Fig. 3. Straight flames barely comply with the current NO_X emission regulations, while V-shaped flames fulfill the requirements with a 50% margin; these two are well-known in the literature. However, distributed combustion offers an 80% margin [4]. This is a huge leap forward since we did not sacrifice the low CO/unburnt fuel emission for low NO_X since all pollutant concentrations were very low. Hence, the advancement of this concept was the principal motivation of our successor OTKA-FK application that received support.

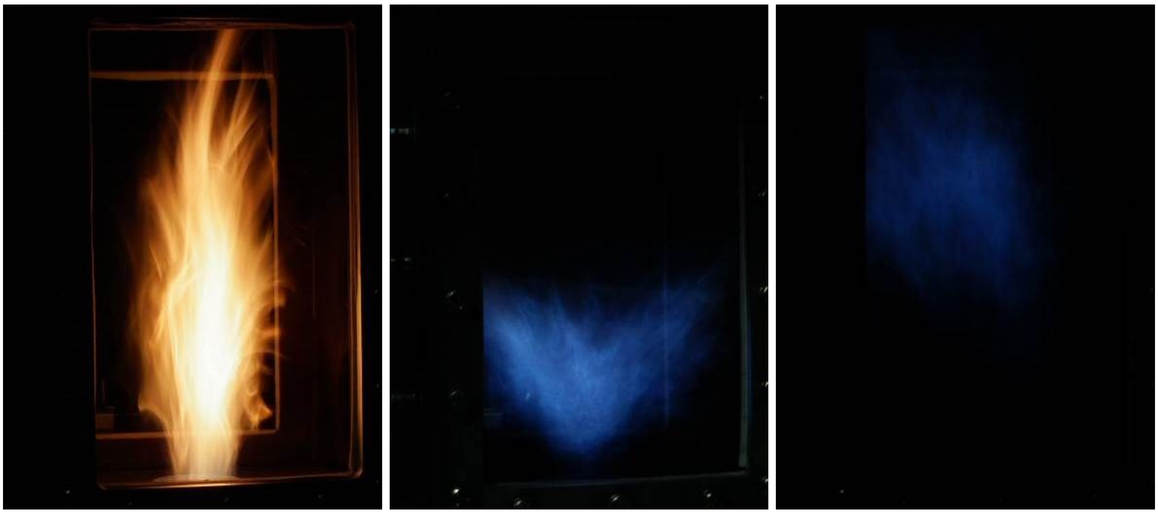

Fig. 3. Flame images with identical camera settings. Straight flame (left), V-shaped flame (middle), and distributed flame (right).

Distributed combustion can be achieved by an MTC burner, shown in Fig. 4, that uses ambient air as an oxidizer, and hence omitting oxidizer dilution by inert gases. This is not limited to the fuel type as it is a concept, but we have only tested liquid and gaseous fuels.

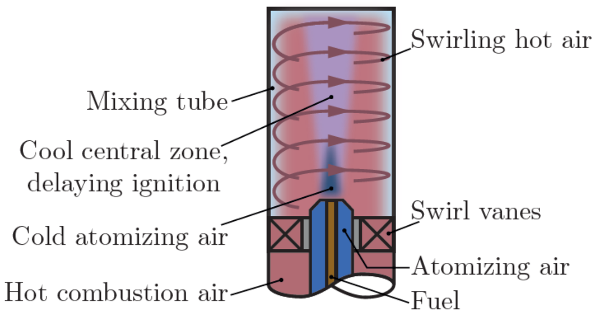

Fig. 4. Operation of the MTC burner [4].

Another critical requirement of advanced combustion concepts is that they must show high fuel flexibility since the share of renewable content in our fuels is increasing, and hence the quality of the renewable part is more difficult to keep within strict limits. Therefore, the MTC combustion system was stressed with *n*-butanol [5] and various biodiesels [3,6] with impressive results. It was recently concluded that even less volatile fuels, such as waste cooking oil biodiesel, can be combusted with distributed flame, but the operation range is narrower. Hence, the burner has to be tailored to the fuel type to allow proper operation. Nevertheless, achieving distributed combustion with more volatile fuels, such as JP-8 [6], is easier.

Due to the promising combustion characteristics, Dr. Milan Malý, a guest researcher from the Brno University of Technology, visited our laboratory during the summer of 2021, bringing a Schlieren system with a high-speed camera and a PDA, shown in Fig. 5. The Schlieren images, corresponding to the flames of Fig. 3, are shown in Fig. 6. The obtained results are under evaluation, and journal papers will be submitted from the acquired 0.5 TB data in the upcoming year. The Schlieren technique was excellent for the analysis of the flame structure, while the PDA is the best available tool for non-invasive measurement with the parallel acquisition of droplet size and velocity in diluted sprays.

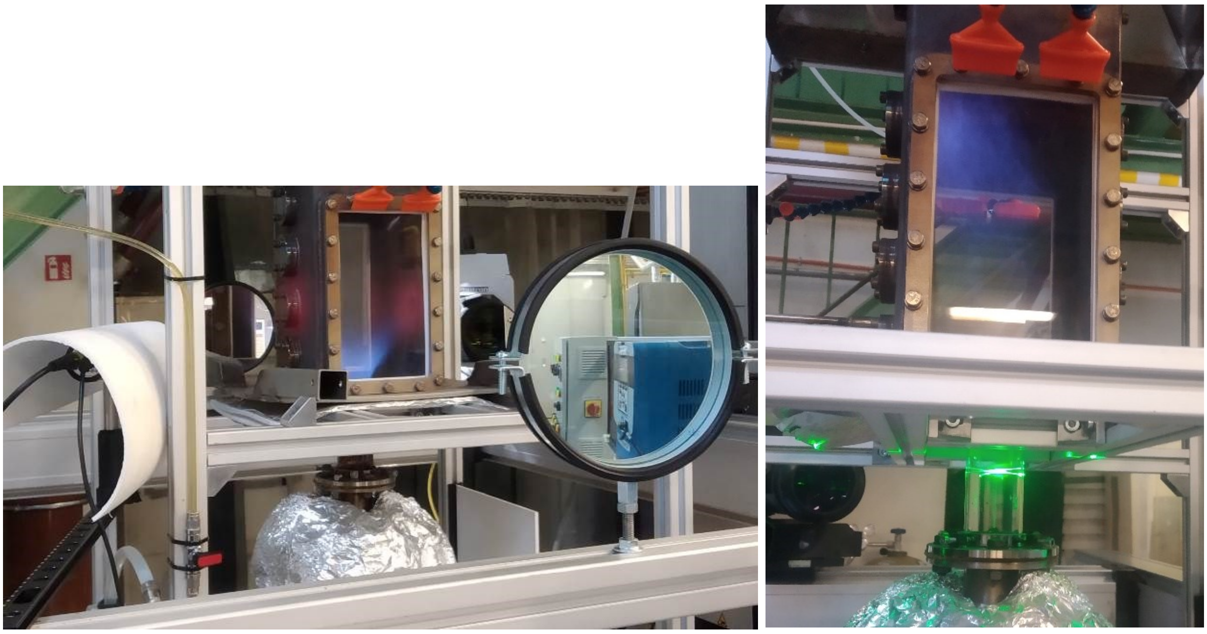

Fig. 5. Schlieren (left) and PDA measurement setup (right).

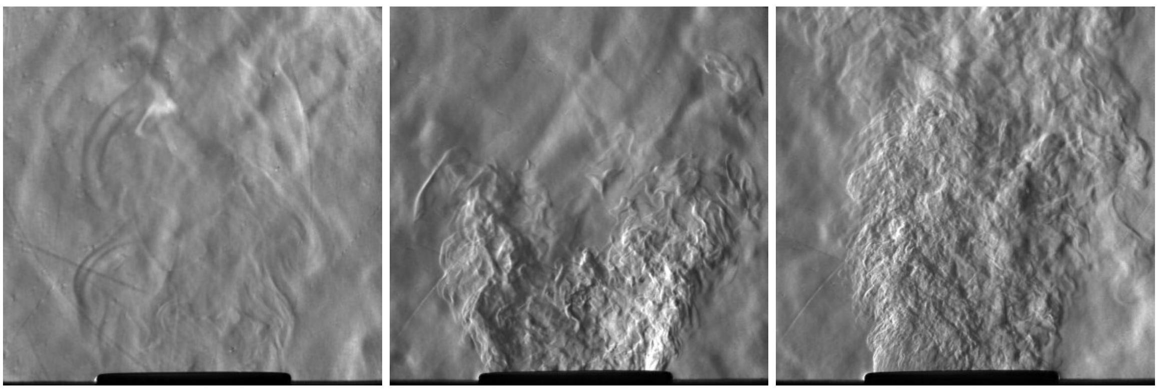

Fig. 6. Schlieren images of straight flame (left), V-shaped flame (middle), and distributed flame (right). The setups are identical as in Fig. 3.

3. Atomization

It is likely that hydrocarbon fuels will remain in use for long decades. However, their feedstock can be an alternative to fossils. Therefore, atomization of four liquids at various conditions was tested to stress the existing mean diameter-estimating formulae available in the literature for airblast atomization [7]. The corresponding measurements under non-reacting conditions were performed at the Brno University of Technology due to the lack of domestic infrastructure (2D PDA). The gathered huge database was evaluated to analyze the histograms of all setups at all measurement points [8]. The spray cone angle estimation requires the proper knowledge of the breakup process and the interaction between the individual droplets and the turbulent, sometimes compressible flow. Nevertheless, it is easier to measure the spray cone angle experimentally. Since there was no estimation formula available for this feature for airblast atomizers, we have derived one [9].

4. Droplet evaporation and measurement of material properties

Evaporation is a natural process occurring in both the environment and machines. Liquid fuels have to be completely vaporized and mixed with the combustion air before the flame front to achieve low-emission combustion. However, evaporation modeling is cumbersome due to the lack of universal models, and more importantly, material properties in the desired temperature range. At first, the estimation methods were stressed, analyzing their sensitivity on evaporation calculation [10]. It was found that the non-dimensional evaporation of *n*-alkanes is similar, allowing the establishment of a general model that may significantly speed up the related numerical calculations [11].

Thermophysical material property data are scarce for renewable fuels due to the uneven yield and their large number. Consequently, data on their blends with fossil fuels are rarely available. Since the reasonable short-term goal to reduce our dependence on fossil fuels is the increase of the share of the renewable content of commercial fuels, these efforts highly support the introduction of the most suitable renewable fuels as additives. Consequently, a wide range of *n*-butanol, ABE, and various biodiesels were tested as neat and blended fuels with commercial biodiesel [12].

5. Online combustion diagnostics

Fast, online combustion control can be performed only via sensing either the light (chemiluminescent) or pressure signal (noise) of the flame [13]. Research in the field of combustion acoustics is critical for lean burners since thermoacoustic instabilities may quickly lead to severe system damage [14]. Instead of the commonly used Fast Fourier Transform, Wavelet Transform of the acoustic signal was used in a paper [15], showing that the high-frequency components of the spectrum feature notable temporal and spectral fluctuations. The next step was to determine the minimal signal length that can be used to characterize the temporal statistics of frequency bands [16]. Unfortunately, this research thread was terminated as my student, Gergely I. Novotni, unexpectedly passed away. However, as mentioned above, the corresponding part of the research plan was completed. It was proven that various fuels could be characterized by a similar spectrum [17], and the setup parameters also have a minor impact on the spectrum if the flame shape is similar [4], which are critical results for acoustic combustion control. These observations led us to a patent application that will hopefully be accepted in Hungary soon, and if we find international interest, the PCT announcement will also be made. The integral of the spectrum, the overall sound pressure level, is also interesting for occupational safety and health since lower noise means a lower physiological load on the human body. Our paper provided a guideline for combustion engineers to properly design swirl burners [18]. Fortunately, distributed combustion also comes with very low noise and low susceptibility to thermoacoustic oscillations [4].

Flame colors usually originate from excited intermittent species, which stabilize via a collision or participate in a further reaction, and ultimately, they emit a single photon. Its wavelength is determined by the possessed excess energy of the electron. Depending on the local conditions, the concentration ratio of the excited species can be used to estimate pollutant emission in real-time instead of waiting for a half-minute to settle, which is typical for all flue gas sensors, including reference methods and electrochemical cells [19].

Future research and use of the results

The ultra-low emission of distributed combustion made it evident that its industrial introduction should be aimed. This fall, we have visited the heating plant of Miskolc, Hungary (MIFŰ), which is owned by Hungarian Electric Works (MVM). They were interested in our patent on combustion control based on acoustic sensing. However, distributed combustion also makes sense in their plant since their principal goal is to cut their NO_X emission to comply with the standards.

Another potential collaborator is WizzAir, who approached us to help them introduce the Sustainable Aviation Fuel to the Hungarian airports to comply with the proposed ReFuelEU European decree. This is strongly connected to our vast experience with renewable fuels and related technologies.

Since our achieved goals are quite impressive, compared to the best available technologies, we have to follow two parallel ways in the future. The first is to borrow or acquire advanced measurement systems to better understand distributed combustion and gain greater international attention in the research community. The second is to search for industrial partners and other supports to employ distributed combustion in practice, hopefully, in jet engines.

Difficulties

Acquiring any part or device was never easy at BME. However, this was manageable in the first three years, regardless that each year came with new rules, which made the acquisition procedure even harder and more inconvenient than before. Since BME introduced the SAP financial system in 2021 and more than tripled the number of intermediate checkpoints, it took six months on average to acquire even a simple and cheap part. Moreover, I still have no information on the financial balance of this grant since the SAP was introduced; I can rely only on my Excel tables, hoping that my numbers are correct; even though I asked for this information each month this year. Therefore, certain parts of the system and several consumables were acquired from our own money to allow continuous work.

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