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Non-MILD distributed combustion of conventional and biodiesel fuels in a novel combustion concept

Thesis booklet by

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1 Objective

In my thesis, I investigated liquid, gaseous, conventional, and biodiesel fuel combustion in a novel low-pollutant emission burner. Even though there are efforts worldwide to reduce CO_2 emissions, practically searching alternatives for combustion, specific industries and transportation will rely on combustion for several decades.

In 2022, The International Energy Agency, IEA, analyzed the renewable energy sector, forecasted the deployment of various transport, heat, and electricity technologies, and identified the critical challenges to the industry [1]. Renewables are expected to dominate the global power mix from 2027. IEA predicts fossil fuel utilization will stagnate in the upcoming decades [2]. At the same time, the energy demand of the world also increases, meaning that the deployed renewable technologies will cover only the growth of the demand.

REPowerEU plan of the European Commission, released in May 2022, proposes to end the reliance on Russian fossil fuels by 2027 [3]. The rising cost of fossil fuels and the tightening regulations on their applicability facilitate the research of alternative fuels. The choice of adequate fuel depends on the availability, cost, ease of handling, and regulations, and it must be compatible with the existing engines and fuel-system requirements.

Our team, the BME Combustion Research Group, has recently developed a new combustion concept called Mixture Temperature-Controlled, MTC, combustion. It was introduced in 2019 [P1 – P3], making distributed combustion of ultra-low NO_X emission available for boilers, furnaces, and gas turbines. The three goals of my research were the following. Firstly, the investigation of the operation and stability of the MTC system through conventional and alternative fuels. Secondly, the application of flame emission spectroscopy, FES, due to its robustness and extensive use in the industry [4, 5]. Thirdly, the evaluation of pollutant emission of all fuels.

2 Low-emission combustion concepts

Three typical turbulent flame images of liquid- or gas-fueled gas turbines, boilers, and furnaces are shown in Fig. 1. Figure 1a represents a straight flame, which is relatively easy to control but features excessive pollutant emissions compared to current regulations. Figure 1b shows a premixed V-shaped flame, which allows a significantly cleaner operation compared to straight flames [6]. Finally, Fig. 1c shows a distributed flame, which requires a larger combustion chamber than the former two flames, features half of the pollutant emissions of V-shaped flames, and significantly lower acoustic loads. Consequently, distributed flames are of great interest to combustion engineers nowadays, potentially the future of combustion for all steady-operating combustion applications.

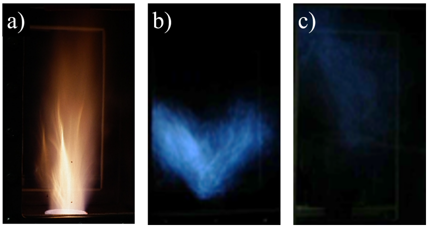

Figure 1: Typical flames of gas turbines, boilers, and furnaces. a) Straight, b) V-shaped, and c) distributed flame.

Moderate or Intense Low-oxygen Dilution, MILD, combustion [7] features distributed flames and can maintain high combustion efficiency while offering almost zero pollutant emissions, including NO_X, making itself a high-potential and promising concept for future use in steady-operating systems [8]. However, its implementation in existing gas turbine technologies, especially in jet engines and usually in industrial gas turbines, inevitably brings complex technical problems to be solved, such as installing a flue gas recirculation or an inert gas supply system. The latest is relatively uneconomical on practical scales, which is the most significant drawback.

The main feature of MTC combustion is that there is no need for external flue gas recirculation or combustion air dilution while producing distributed flames with low CO and NO_X emissions. The mixture is sufficiently homogeneous to have a less intense heat release during combustion and qualitatively approach MILD combustion.

3 Materials and methods

The investigated fuels are listed in Table 1, and the MTC test rig is shown in Fig. 2. Two experiments were performed; the corresponding conditions are shown in Table 2. The goal of the chemiluminescent measurements was the optical mapping of different flame shapes. Therefore, the parameters were selected to achieve straight and V-shaped flames as references and distributed flames to approach flameless conditions.

Table 1: Investigated fuels.

Category	Fuel	Abbreviated
Fossil	Natural gas	NG
	Standard military aviation fuel	JP-8
	Diesel	D
Biodiesel	Coconut oil methyl ester	CME-B100
	Palm oil methyl ester	PME-B100
	Blend of 30/40% waste cooking oil and 70/60% rapeseed oil	$WCO_{30/40}$-B100
Blends	25/50/75 V/V% biodiesel, 75/50/25 V/V% diesel	B25/B50/B75

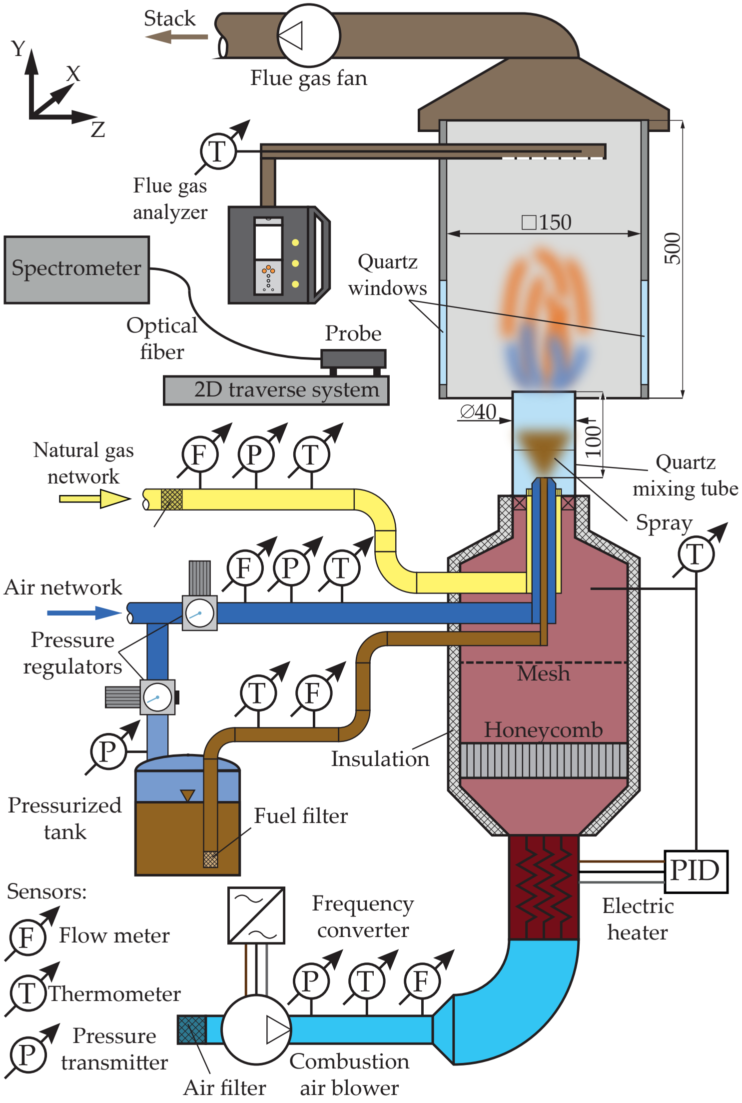

Figure 2: The test rig.

Table 2: Outline of the test conditions.

Parameter	Value/range	
Experiment no.	1	2
Thermal power [kW]	13.3	13.3
Fuel-to-air equivalence ratio, ϕ [1]	0.8	0.57 – 0.86
Combustion air preheat temperature, T_{ca} [°C]	T_{amb} – 350	225
Atomizing gauge pressure, p_g [bar]	0.3 – 0.9	0.3 – 0.9

A typical spectrum of hydrocarbon flames is introduced through an NG flame, shown in Fig. 3, in the 187-1100 nm range. According to the literature and our measurements, the investigated radicals and their highest intensity peak(s) are shown in Table 3.

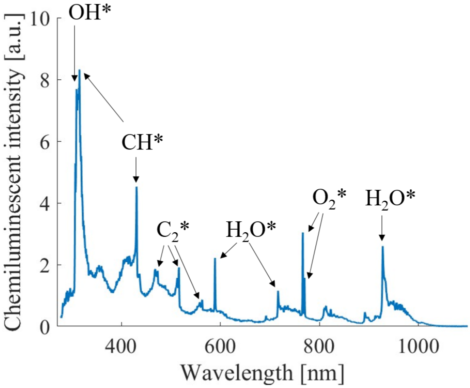

Figure 3: Chemiluminescent spectrum of a natural gas flame.

Table 3: The investigated radicals.

Radical	Wavelength according to Gaydon [9] [nm]	Mean wavelength of high intensity peaks in our measurements [nm]
OH^*	309.04	310.66
CH^*	431.42	430.35
$C_2{}^*$	516.52	515.62
H_2O^*	588.02, 590.02, 927.7	589.23, 927.97
O_2^*	768.38	766.53

4 Results and thesis points

Straight, V-shaped, and distributed flame shapes were observed during the combustion tests. Since fully turbulent combustion was performed, the flame shape was altered in some setups, with a transition frequency of about 0.5-3 Hz. Flame shapes at all the investigated operating points are shown in Table 4. Thesis points 1 and 2 highlight the fuel sensitivity of distributed combustion in the MTC burner and aim to facilitate the spread of the concept in industrial applications.

Table 4: Flame shapes at the operating points. a-b) $\phi = 0.8$, c) $T_{ca} = 225$ °C. Abbreviations and colors referring to the flame shapes: s (yellow) – straight, d (blue) – distributed, v (red) – V-shaped, transitory operations: (green) – straight and distributed, (orange) – straight and V-shaped, (purple) – distributed and V-shaped, (brown) – straight, distributed and V-shaped. (gray) – no stable combustion.

a)

Fuel	T_{ca} [°C]	p_g [bar]				
		0.3	0.45	0.6	0.75	0.9
NG	350	s	s	s	s	s
	300	s	s	s	s	s
	250	s	s	s	s	s
	200	s	s	s	s	s
	150	s	s	s	s	s
JP-8	350	s	s	s	s	s
	300	s	s	s	s	s
	250	s	s	s	s	s-d
	200	■	d	d	d	d
	150	d	d	d	d	d
D	350	s	s	s	s	s
	300	s	s	s	s	s
	250	s	s	s-d	d	d
	200	s	s	d	d	d
	150	s	s	d	d	d

b)

Fuel		CME					PME					WCO_{40}				
	T_{ca} [°C]	p_g [bar]					p_g [bar]					p_g [bar]				
		0.3	0.45	0.6	0.75	0.9	0.3	0.45	0.6	0.75	0.9	0.3	0.45	0.6	0.75	0.9
B25	350	s	s	s	s	s	s-d	s-d	s-d	s-d	s-d	s-d	s-d	s-d	s-d	s-d
	300	s	s	s	s	s	s	s-d	s-d	s-d	s-d	s-v	s-d	s-d	s-d	s-d
	250	s	s	s	s	s	s	s	s-d	s-d	d	s-v	s-d	s-d	s-d	s-d
	200	s	s	s	d	d	s	s-d	d	d	d	s	s	s	d	d
	150	s	s	s	s	d	s	s-d	s-d	d	d	s	s	d	d	d
B50	350	s	s	s	s	s	s	s	s-d	s-d	s-d	s-d	s-d	s-d	s-d	s-d
	300	s	s	s-d	d	d	s	s-d	s-d	s-d	s-d	s-v	s-d	s-d	s-d	s-d
	250	s	s-d	d	d	d	s	s-d	s	s	s	s-v	s-d	s-d	s-d	s-d
	200	s	s	s	d	d	s	s	s	s	s	s	s	s	s	s
	150	s	s	d	d	d						s	s	s	s	s
B75	350	s	s	s-d	d	d	s	s	s-d	s-d	s-d	s-d	s-d	s-d	s-d	s-d
	300	s	s-d	d	d	d	s	s	s	s-d	s-d	s-d	s-d	s-d	s-d	s-d
	250	s-d	d	d	d	d	s	s	s	s	s	s-d	s-d	s-d	s-d	s-d
	200	s	d	d	d	d	s	s	s	s	s-d	s	s-d	s-d	s-d	s-d
	150															
B100	350	s	s	s	s	s	s	s-d	s-d	s-d	s-d	s-v	s-d	s-d	s-d	s-d
	300	s	s-d	d	d	d	s	s-d	s-d	s-d	s-d	s-v	s-d	s-d	s-d	s-d
	250	s	d	d	d	d	s	s	s	s	s	s-v	s-d	s-d	s-d	s-d
	200	s	s-d	d	d	d	s	s	s	s	s-d	s	s-d	s-d	s-d	s-d
	150															

c)

Fuel	ϕ [1]	p_g [bar]				
		0.3	0.45	0.6	0.75	0.9
D	0.86	s	s	s	s	s
	0.76	s	s-d	d	d	d
	0.67	s-v	s-d	d	d	d
	0.57	v	d	d	d	d
WCO$_{30}$-B25	0.86	s	s	s	s	s
	0.76	s	s	s	s	s
	0.67	v	s-d	d	d	d
	0.57	s-v	v-d	d	d	d
WCO$_{30}$-B50	0.86	s	s	s	s	s
	0.76	s	s	s-d	s-d	s-d
	0.67	v	s-v-d	s-d	d	d
	0.57	s-v	v	d	d	d
WCO$_{30}$-B75	0.86	s	s	s	s	s
	0.76	s-v	s	s	s-d	s-d
	0.67	v	s-d	d	d	d
	0.57	s-v	v	d	d	d
WCO$_{30}$-B100	0.86	s	s	s	s	s
	0.76	s-v	s-d	s-d	s-d	s-d
	0.67	v	s-d	s-d	s-d	s-d
	0.57	v	v	d	d	d

Thesis point 1:

Distributed combustion in the Mixture Temperature-Controlled concept is feasible with the following fuels: JP-8 standard military aviation fuel (MIL-DTL-83133, British Defence Standard 91-87), standard diesel fuel (EN 590), methyl ester of coconut and palm oils, two blends of waste cooking oil and rapeseed oil of 40 and 30% waste cooking oil share, and the blends of these biodiesel fuels with diesel fuel in 25, 50 and 75 V/V% biodiesel share. [P4 – P10]

Table I shows the test parameters of distributed combustion. The thermal power was 13.3 kW for all tests.

Table I: Test parameters of distributed combustion. Note the following abbreviations. D – diesel fuel, CME – methyl ester of coconut oil, PME – methyl ester of palm oil, WCO_{40} and WCO_{30} – blends of waste cooking oil and rapeseed oil of 40 and 30% waste cooking oil share, respectively. B25, B50 and B75 – 25, 50 and 75 V/V% content of a biodiesel blended with D.

Fuel	Combustion air temperature [°C]	Atomizing pressure [bar]	Equivalence ratio [1]
JP-8	150	0.3-0.9	0.8
	200	0.45-0.9	0.8
D	150-200	0.6-0.9	0.8
	250	0.75-0.9	0.8
	225	0.45-0.9	0.57
	225	0.6-0.9	0.67-0.76
CME	200, 300	0.6-0.9	0.8
	250	0.45-0.9	0.8
CME-B75	200-250	0.45-0.9	0.8
	300	0.6-0.9	0.8
	350	0.75-0.9	0.8
CME-B50	150, 250	0.6-0.9	0.8
	200, 300	0.75-0.9	0.8
CME-B25	150	0.9	0.8
	200	0.75-0.9	0.8
PME-B25	150	0.75-0.9	0.8
	200	0.6-0.9	0.8
	250	0.9	0.8
WCO_{40}-B25	150	0.6-0.9	0.8
	200	0.75-0.9	0.8
WCO_{30}	225	0.6-0.9	0.57
WCO_{30}-B75	225	0.6-0.9	0.57-0.67
WCO_{30}-B50	225	0.6-0.9	0.57
	225	0.75-0.9	0.67
WCO_{30}-B25	225	0.6-0.9	0.57-0.67

Thesis point 2:

The distributed combustion in the Mixture Temperature-Controlled concept of methyl ester of coconut oil, CME, blended with standard diesel fuel (EN 590) in 75 V/V% CME share results in a wider distributed combustion regime than the combustion of neat CME or diesel fuel. [P5, P7]

Relevant test parameters are shown in Table II. The thermal power was 13.3 kW, and the fuel-to-air equivalence ratio was 0.8 for all tests.

Table II: Distributed combustion of diesel fuel, D, methyl ester of coconut oil, CME, and their blend of 75 V/V% CME share, CME-B75.

Fuel	Combustion air preheat temperature [°C]	Atomizing gauge pressure [bar]
D	150-200	0.6-0.9
	250	0.75-0.9
CME	200, 300	0.6-0.9
	250	0.45-0.9
CME-B75	200-250	0.45-0.9
	300	0.6-0.9
	350	0.75-0.9

Spectral characteristics of distributed flames were compared to straight and V-shaped flames. Complete combustion of straight and V-shaped flames occurred within the investigated zone, indicated by all radicals listed in Table 3. As a distributed flame became leaner, the centers of the radical emissions shifted downstream in the combustion chamber due to the increased air flow rate and the lower reactivity of the mixture. The goal was to localize the reaction zone quantitatively. Therefore, the distribution of the intensity ratios of the investigated radicals was also evaluated. Figure 4 shows the OH^*/CH^* intensity ratios in the case of the leanest and richest investigated distributed D flames.

The sampling points are marked with a + sign. Thesis point 3 summarizes the main results of the spectral measurements.

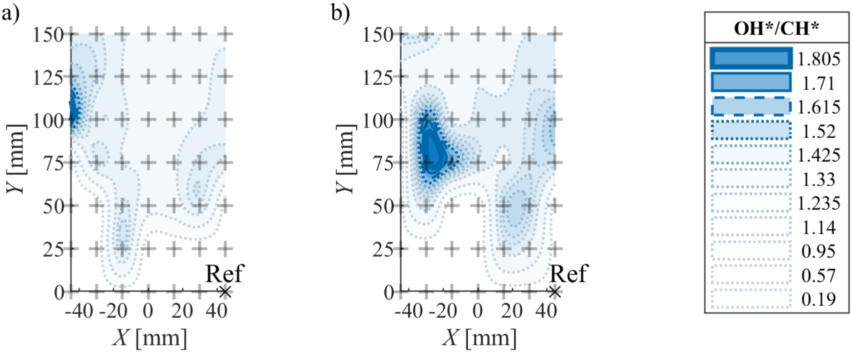

Figure 4: OH*/CH* intensity ratios of distributed D flames of a) $\phi = 0.76$, and b) $\phi = 0.57$.

Thesis point 3:

Distributed standard diesel fuel (EN 590) flames of the Mixture Temperature-Controlled concept spectrally occupy a large volume in the combustion chamber without featuring any typical flame shape or being sensitive to the fuel-to-air equivalence ratio of 0.57-0.76. [P11]

The spatial distribution of the investigated radicals shows that the chemical conversion processes of combustion take place in a large volume with several intensity peaks for each radical. If the reaction zone boundaries are checked, the contour lines of distributed flames encompass broad areas instead of well-localized shapes, characteristic of straight and V-shaped flames. The strong H_2O^* emission peaks of 588.02 and 590.02 nm appeared as a single, merged intensity peak at 589 nm in the measured spectrum; therefore, this double peak is referred to as a peak at 589 nm wavelength. The spatial distribution of six respective radicals, OH* at 311 nm, CH* at 430 nm, CH* at 516 nm, O_2^* at 767 nm, and H_2O^* at 589 and 928 nm were investigated.

The NO and CO emissions of the investigated fuels were evaluated in several operation points concerning the flame shapes and compared to the strictest limitations given in the 2015/2193 EU directive [10] and in the 53/2017 Hungarian decree [11], respectively. In most measurement setups, CO emission remained below 5 mg/Nm^3 at 15 V/V% flue gas O_2 level, which equals two times the sensor uncertainty and is a magnitude lower value than the strictest limit. The flame shape primarily governed the NO emission and that of distributed flames concentrated below 10 mg/Nm^3, shown in Fig. 5.

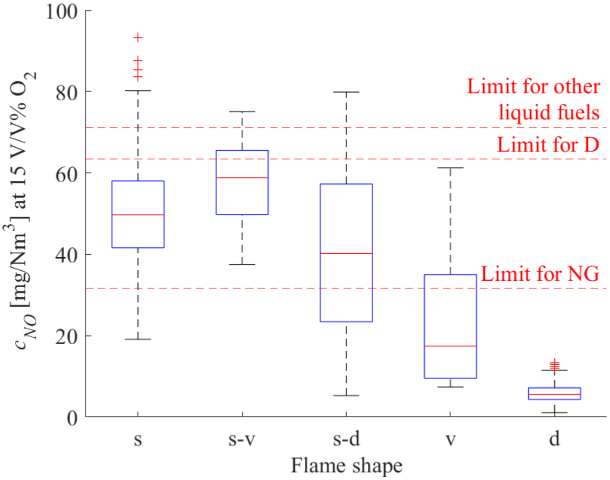

Figure 5: Boxplots of NO emission according to the flames shapes. s – straight, s-v – transient of straight and V-shaped, s-d – transient of straight and distributed, v – V-shaped, d – distributed flames.

Thesis point 4:

The investigated distributed flames of the Mixture Temperature-Controlled concept emit, on average, 8.8% NO of the limit given in the 2015/2193 EU directive for gas oil combustion in medium-sized combustion plants (1-50 MW of total rated thermal input). The flame

shape primarily affects the NO emission in the Mixture Temperature-Controlled concept, while the fuel type has low influence unless distributed combustion is achieved. Besides NO, the CO and UHC emissions are also low. [P4 – P10]
During the tests of distributed flames, the thermal power was 13.3 kW, various fuel-to-air equivalence ratios were selected in the range of 0.57-0.86, various combustion air preheat temperatures were set from ambient temperature to 350 °C, and various atomizing gauge pressures of the atomizing air were applied in the range of 0.3-0.9 bar. The investigated fuels featuring distributed flames were the following. JP-8 standard military aviation fuel (MIL-DTL-83133, British Defence Standard 91-87), standard diesel fuel (EN 590), D, methyl ester of coconut oil, CME, – neat and blended with D in 25, 50 and 75 V/V% CME share, methyl ester of palm oil, PME, blended with diesel fuel in 25 V/V% PME share, a blend of waste cooking oil and rapeseed oil of 40% waste cooking oil share, WCO_{40}, blended with D in 25 V/V% WCO_{40} share, and a blend of waste cooking oil and rapeseed oil of 30% waste cooking oil share, WCO_{30}, blended with D in 25, 50, and 75 V/V% WCO_{30} share.

CO and NO emissions of distributed flames were also compared to the data on MILD combustion in the literature. Figure 6 shows that similarly low NO emission was measured in the same ϕ range for D, kerosene, and ethanol flames by Sharma et al. [12, 13], Reddy et al. [14, 15], and Ye et al. [16], respectively, as for the distributed flames of the MTC burner. At lower ϕ-s, ϕ=0.2-0.3, two biodiesel, BD, flames of lower combustion power were able to emit NO below 10 mg/Nm^3, investigated by Sharma et al. [12]. MILD combustion of BD and sunflower oil methyl ester, SME, – neat and blended with D in 50 V/V%, resulted in higher NO emissions than the distributed flames of the MTC burner. NO emissions for MILD CH_4 flames were reported by Yetter et al. [17]. At both operating points, the NO emission exceeds the limit for NG combustion, and it is more than four times the NO emission of the distributed flames of the MTC burner.

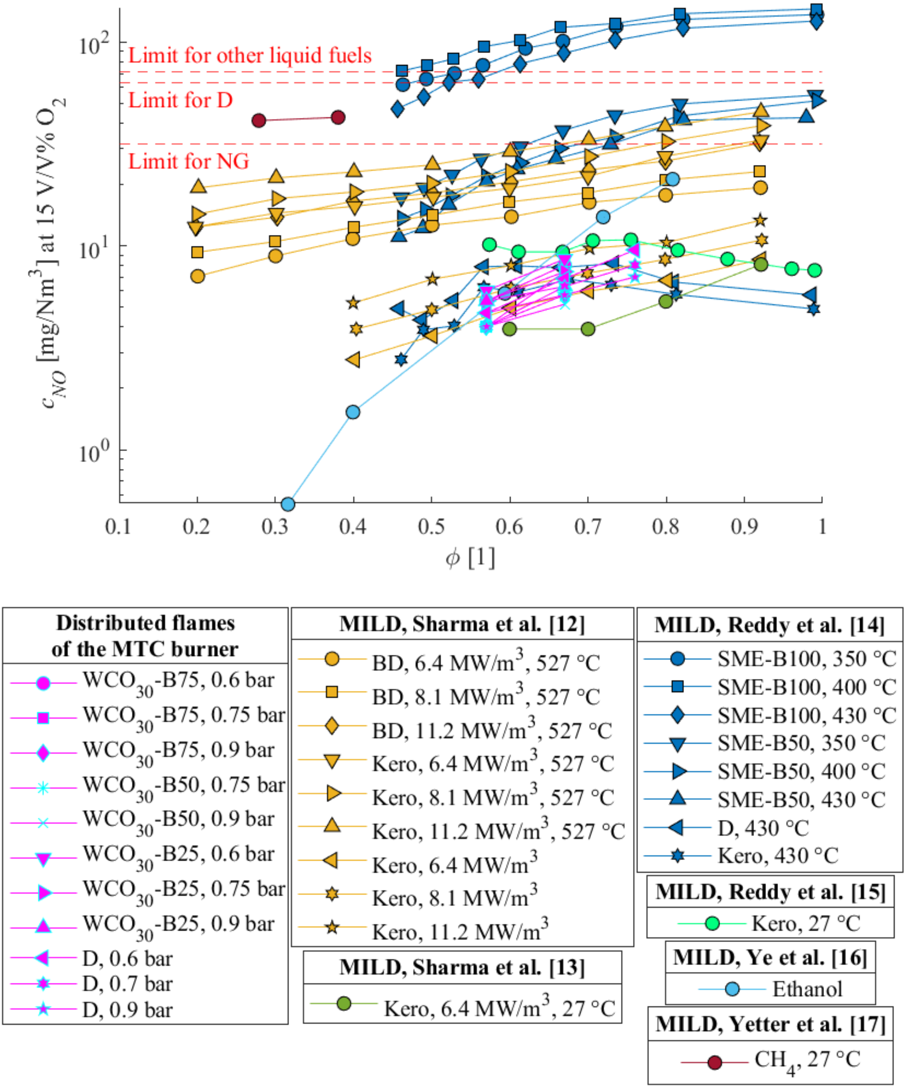

Figure 6: Variation of NO emission with ϕ of the distributed flames of the MTC burner, and MILD combustion of the literature.

Thesis point 5:

Distributed flames of the Mixture Temperature-Controlled concept emit two times lower NO in the same fuel-to-air equivalence ratio range of 0.57-0.76 than MILD biodiesel flames of the lowest NO emission of the literature, reported by Sharma et al. [R1], and similarly low NO emission in the same fuel-to-air equivalence ratio range as MILD flames of diesel fuel and kerosene reported in the literature [R1 – R6]. [P4 – P10]

Distributed combustion was achieved with the following fuels. JP-8 standard military aviation fuel (MIL-DTL-83133, British Defence Standard 91-87), standard diesel fuel (EN 590), D, methyl ester of coconut oil, CME, – neat and blended with D in 25, 50 and 75 V/V% CME share, methyl ester of palm oil, PME, blended with diesel fuel in 25 V/V% PME share, a blend of waste cooking oil and rapeseed oil of 40% waste cooking oil share, WCO_{40}, blended with D in 25 V/V% WCO_{40} share, and a blend of waste cooking oil and rapeseed oil of 30% waste cooking oil share, WCO_{30}, blended with D in 25, 50, and 75 V/V% WCO_{30} share.

[R1]: S. Sharma, H. Pingulkar, et al. *Combustion and Flame*, 193:61-75, Jul 2018.

[R2]: S. Sharma, R. Kumar, et al. *Fuel*, 199:229-238, 2017.

[R3]: V.M. Reddy, P. Biswas, et al. *Fuel Processing Technology*, 118:310-317, 2014.

[R4]: V M. Reddy, D. Sawant, et al. *Proceedings of the Combustion Institute*, 34(2):3319-3326, 2013.

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[R6]: J. Ye, P.R. Medwell, et al. *Applied Energy*, 151:93-101, 2015.

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