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Data Article

Dataset of temperature, heat flux and infrared emission from flat premixed laminar methane-air flames

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ABSTRACT

To enable the use of flat flame burners in the context of fire resistance testing, we present a data set covering temperature, infrared emission and heat 15 mm above the burner. A laminar premixed methane-air flame is characterized for eleven different fuel/air ratios, ranging from lean (0.9) to rich (1.45), extending an existing a widely used reference [1]. We provide complementing flame temperature readings from thermocouple measurements that can be used for calibration. In addition, broadband flame optical emissions are acquired in the visual (VIS) and the infrared (IR) spectral region. Chemiluminescence measurements reveal the spatial distribution of the OH* radicals. Heat flux density measurements with a water-cooled gauge are also provided. Finally, the expected species concentration, velocity, temperature are obtained from chemical kinetics calculations. Ambient conditions and burner control parameters are presented as supplementary data.

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Specifications Table

Subject	Mechanical Engineering
Specific subject area	Combustion research and flame diagnostics
Type of data	Table / Image / Graph / Figure / Code / Text
How data were acquired	Multi-spectral IR camera: Telops MS M350 with filter wheel Heat-flux sensor and acquisition: Hukseflux SBG01 (max. $200 \times 10^3 W/m^3$) and National Instruments USB-6001 Mass flow controller: Hastings HFC-202 Photographs: Nikon D750 Lens: Nikon Rayfact UV lens PF10545MF-UV Image intensifier: Invisible Vision 1850-10 Highspeed camera: Photron Fastcam Mini AX200 Filter: Andover 310nm bandpass filter, HBW 10 nm (310FS10-50) Water temperature: Type T thermocouples and Omega HH509R handheld digital thermometer Flame temperature: Coated type R thermocouples with National Instrument chassis cDAQ-9171 and temperature input module NI-9213 Humidity, barometric pressure and ambient temperature: Bosch BME280 with Arduino Uno.
Data format	Raw Analyzed Calculated
Parameters for data collection	Individual data sets refer to enumerated standard flames of different air/fuel ratios and gas flow rates. The equivalence ratio is varied between 0.9 and 1.45. Measurements were reproduced several times, over the course of a week, for thermocouple, infrared imaging and heat flux density measurements. Ambient laboratory conditions are provided.
Description of data collection	After flame stabilization, imaging data was acquired with the IR camera, the OH^* system and the DSLR camera. Cooling water temperature for the burner and the heat flux gauge was measured with a handheld thermometer (Omega HH509R). The heat flux sensor was swivel-mounted and moved in the flame for approx. 15 seconds. The flame temperature was probed with alumina-coated thermocouples.
Data source location	Institution: Polytechnique Montréal City/Town/Region: Montréal/Québec Country:Canada Latitude and longitude (and GPS coordinates, if possible) for collected samples/data: 45°30′15.7″N 73°36′45.2″W; G93P+PX (Google Plus Code)
Data accessibility	Repository name: Mendeley Data Data identification number (DOI): 10.17632/jvvvgpdy48.5 Direct URL to data: https://data.mendeley.com/datasets/jvvvgpdy48/5

Value of the Data

- These data extend an existing data set gathered using the same laminar premixed flat burner. This burner is a widely available research tool and produces nearly one-dimensional flames. Although this tool is extensively used for the validation of theoretical combustion models, it now finds applications in fire resistance testing where idealized flame are desirable. For this purpose, information on temperature distribution profiles, heat flux density and spatial uniformity is required.
- The data is of interest to a broad research community using such standard burner-stabilized 1D flat flames. The diagnostic tools used here for flame characterization are not as accessible as the burner themselves. The multispectral infrared images in combination with two-colour pyrometric techniques can be used to obtain flame temperature and emissivity mappings.
- Flame temperature data from thermocouples help to calibrate experimental conditions against reference conditions as they can be easily reproduced.
- The data can be used to support numerical model validation, to calibrate test conditions and to provide reproducible flame environments.

1. Data Description

McKenna type flat flame burners create a good approximation of the idealized one-dimensional premixed flame. These burners are hence widely available and used for fundamental combustion studies. In a previously published report by the German Aerospace Center (DLR), Weigand et al. [1] considered a "standard" flames with methane as the fuel and dry air as the oxidizer. They provided point measurement of flame temperature at a fixed position above the burner centre using Coherent anti-Stokes Raman Scattering (CARS). They also implemented a numerical model of the flame, using CHEMKIN/PREMIX, and extracted the adiabatic flame temperature for 22 fuel-to-air ratios. Data in the present report complements a subset of eleven different premixed methane-air flames from the work of Weigand et al. [1], implementing additional diagnostics tools. The same burner is used, at ambient pressure. A measurement location of 15 mm above the burner was chosen in accordance with the reference data set as it allows good optical access and time temperature gradients become negligible [1].

The data is stored on the Mendeley repository and grouped by information-type into seven folders. The naming convention for the individual file types is outlined in Table 1, where the two-digit condition/flame numbers (##) are consistent with the ones introduced by Weigand et al. [1]. The files obtained from numerical calculations (folder 6) contain the fuel/air ratio Φ as a two-digit float number (YYY) with the decimal point omitted. For some measurements, supplementary data (*Supp.*), e.g. filter specifications or ambient conditions, are provided in a separate folder. Large data sets have been compressed (*Compr.*). More information on each folder and the data contained is provided in the following.

1.1. Heat flux density

The measurements were acquired at a rate of 5 Hz and the probe was placed for an average of 10 s into the flame. The acquisition started before the probe was placed in the flame and continued for a few seconds after its removal. Each file contains four columns with the first being date and time. The second is the acquired voltage signal U [mV]. The third (Q [W]) and fourth (Q [kW]) provide the heat flux density converted using the instrument sensitivity S = 1.72E-7 and the formula $Q = U/S$. The factory calibration uncertainty under reference conditions is $\pm$6.5%.

1.2. OH-chemiluminescence*

Pictures were taken at 1000 fps for a total of approximately 2 s. However, to limit file size, only subsets of the data spanning 250 ms or 100 ms are provided. The high-speed camera system was positioned at approximately one meter from the burner centre and horizontally aligned with the burner plane.

Table 1
Naming convention and organizational layout for the data provided on Mendeley Data. The folder *05_Supplementary_Data* is intentionally left out because the names of the files it contains do not follow a specific logic.

Folder	Information	Naming logic	Supp.	Type	Compr.
01	Heatflux density	20200511_SBG_FFC_condition##		.csv	
02	OH* chemiluminescence	FFOH_flame##_100	x	.jpg,.CIHX	x
03	Photo (normal)	20201105_FFcond__##		.jpg	
03	Photo (tilted)	FFOH__20201120_00##		.jpg	
04	IR images	IR_FFC_flame##	x	.txt,.jpg,.hcc	x
06	Cantera calculations	CH4_phiYYY_GRI_mix		.csv	
07	Thermocouple data	FF_TC1_cond##		.txt	

1.3. Pictures

Photographs were taken with a DSLR camera and a 105 mm macro-lens, with an F-number of 3.5, ISO6400 and 1/30 s^{-1} shutter speed (*PIC_FF_F3-5_ISO6400_normal*). The camera is horizontally aligned with the burner plane so that the flame sheet is reduced to a line. A second set of pictures was taken at a slightly downward inclined angle (<10°), to give a better impression of the flame sheet, with F4.0, ISO2400 and 1/20 s^{-1} shutter speed (*PIC_FF_F4_ISO2500_tilted*). The file naming of the two folders follows the convention outlined in Table 1 and examples of pictures taken at both angles can be seen in Fig. 2b and d.

1.4. Thermal imaging

Fig. 1 shows examples of the in-band radiance (IBR) response of a stoichiometric standard flame at ambient pressure without co-flow. The infrared camera is equipped with a filter wheel, allowing the splitting of the scene radiance in different bands. Specific spectral ranges of interest can thus be isolated, with data from four different filters provided (Table 2). Filter 4 is centered on water vapor emission (Fig. 1-left) and provides a qualitative visualization of the temperature distribution in the reaction zone. The filter centered on the carbon-dioxide red spike (fig. 1-center) shows a similar pattern, but with a stronger signal. Filter 2 (Fig. 1-right) is broadband with a neutral density attenuation (optical density OD=1.65), providing good contrast both in the reaction zone and in the exhaust plume.

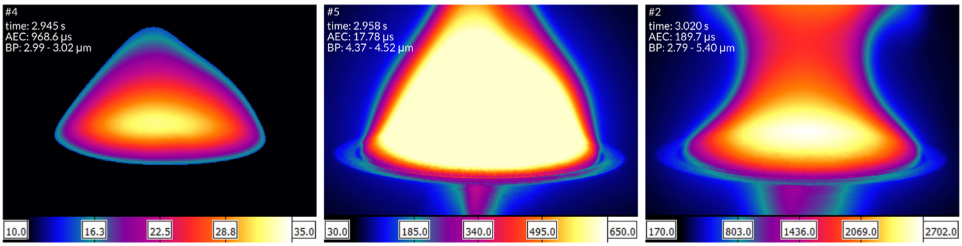

Fig. 1. IBR response of a stoichiometric ($\phi = 1.0$) standard flame (condition 03) through different filters: Filter 4 (left)-H_2O, filter 5 (center)-CO_2, filter 2 (right)-broadband, ND 1.65. The position in the filter wheel and its turning speed cause a relative time delay between filter 4 and 5 of 13 ms and between filter 5 and 2 of 62 ms at 80 Hz acquisition frequency.

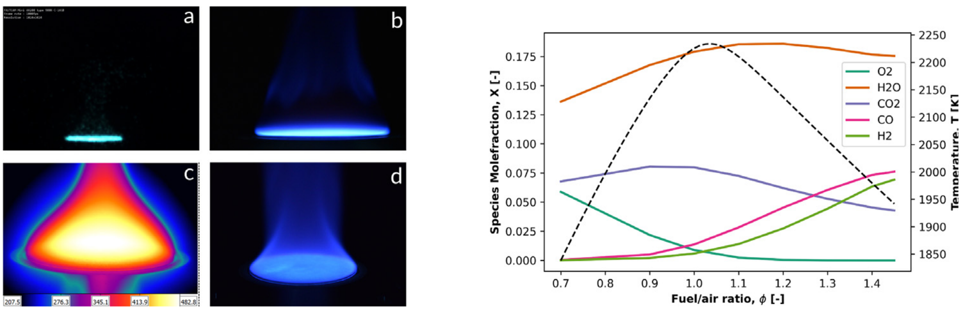

Fig. 2. Examples of data presented: Left: Flame images for a slightly rich flame at $\Phi = 1.1$. (a) OH*-chemiluminescence, (b) photo of the visible spectrum normal to flame plane, (c) IR picture through CO_2-filter with automatic color gradient legend in [°C], (d) photo in the visible spectrum inclined relative to flame plane. *Right:* Species and temperature evolution over the investigated range of Φ in the region of interest (z= 15mm).

Table 2
Specification and wavelength range of the spectral filters. The position (Pos.) refers to the camera filter wheel.

Filter no.	Description	λ_{min} [nm]	λ_{max} [nm]	χ [%]	T [° C]
1	Sapphire window (Broadband)	1500	5400	95.00	0-320
2	Neutral density filter, OD 1.65 (Broadband)	1500	5400	2.33	200-1000
4	NPB-3010-40 (H_2O)	2987	3038	70.90	320-1300
5	NBP-4450-150 (CO_2 Red spike)	4382	4597	85.00	120-800

The signal is acquired for a 388 px × 260 px window. The acquisition frequency is 80 Hz for all sets and each sequence covers typically a few seconds for a given flame condition. The automatic exposure control (AEC) function of the Telops® Reveal-IR tools was used. The data is provided in three different formats. The *hcc* files, a proprietary file format, can be opened with the IR-Reveal software [2]. Doing so allows to access the data for each filter wheel position separately for post-processing and analysis. Each measurement sequence has also been exported as jpg using the standard color palette and showing the pictures taken through filter no. 1, 2, 4, and 5 in a 2 × 2 matrix. The individual frames have also been exported in ASCII format, containing acquisition-related information in the header. The specifications for each filter are provided as supplementary data.

1.5. Supplementary data

The ambient laboratory conditions in close proximity to the flame sheet, including relative humidity, barometric pressure and temperature, are provided as log text files (<Date>_TPH_log.txt). With an acquisition frequency of 1 Hz, the entire period of the measurement campaign is covered. The OH-Filter specifications are supplied in *Andover_310FS10-50.csv* and the IR camera filter wheel configuration including filter characteristics in *IR_camera_filter-specifications.xlsx*.

1.6. Chemical kinetics calculations

Chemical kinetics 1D calculations [3] are made using the Cantera software package [4], which relies on the nine coefficients NASA correlations for transport properties [5]. The simulations yields the theoretical mole fractions, flow velocity (gas velocity normal to the flame front), temperature and density as a function of position along the burner center line for different values of Φ. Some examples are shown on the left graph in Fig. 2. The outlet conditions for the gas mixture are set at room temperature (300K) and standard pressure (101.325 kPa), with the computational domain spanning 30 mm above the burner exit. CSV files for each of the eleven fuel/air ratios contain the spatial evolution of the properties across the domain.

1.7. Flame temperature data

A type R thermocouple (Fig. 3) is moved to the center of the flame with a motor-driven stage. The measurement period of 10 s is repeated three times for each condition. The temperature data is provided in °C alongside with the Gardon gauge cooling water temperature. The measurements have not been corrected for radiation losses. A summary of the calculated and measured temperature data at a height of 15 mm above the burner plate is given in Table 3. The average difference between the CHEMKIN calculations from Weigand et al. [1] and the Cantera results for similar conditions (T_{ad}) is 31 K and can be attributed to differences in the numerical implementation. The theoretical (adiabatic) temperature at this position is on average 263 K

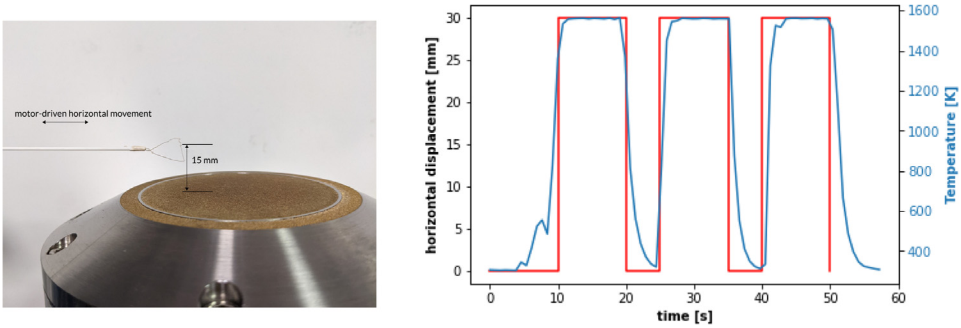

Fig. 3. *Left*: A coated thermocouple is positioned 15 mm above the burner plate. *Right:* The probe is moved from a position outside the flame to a position approximately at the burner center with a motor stage. The position is held in the flame for 10 s, followed by a 5 s break outside the flame, for at total of three cycles.

Table 3
Measured and calculated properties at a position z = 15 mm above the burner plane for eleven flame conditions. The numbers in the first column are congruent with the condition numbers in [1]. In the following, u denotes the gas velocity [m/s], X the product-specific molar fractions [mol/mol], ϕ is the equivalence ratio, $\dot{Q}$ the heat flux density [kW/m^2] and T_{ad} and T_{TC} are the numerically calculated and probed temperature in Kelvin. The thermocouple data represents the average of three acquisitions of 10 s each, for each condition.

	Burner parameter			Measured		Calculated							
	CH_4	Air	ϕ	$\dot{Q}$	T_{TC}	T_{ad}	u_{av}	$X(O_2)$	$X(N_2)$	$X(H_2O)$	$X(CO_2)$	X(CO)	$X(H_2)$
1	1.100	15.00	0.70	25.4	N/A	1835	1.2	0.059	0.735	0.136	0.068	0	0
3	1.310	12.40	1.00	33.6	1488	2163	2.8	0.009	0.706	0.179	0.080	0.014	0.006
4	1.310	11.31	1.10	34.4	1481	2159	2.8	0.002	0.691	0.185	0.072	0.028	0.014
5	1.310	10.40	1.20	39.1	1437	2104	2.5	0	0.674	0.186	0.062	0.045	0.027
6	1.420	15.00	0.90	44.8	1459	2101	2.4	0.022	0.718	0.168	0.081	0.005	0.002
9	1.733	14.96	1.10	37.1	1535	2159	2.8	0.002	0.691	0.185	0.072	0.028	0.014
10	1.735	15.00	1.10	45.6	1526	2159	2.8	0.002	0.691	0.185	0.072	0.028	0.014
11	1.733	13.70	1.20	N/A	1334	2104	2.5	0	0.674	0.186	0.062	0.045	0.027
12	1.733	11.80	1.40	N/A	1515	1976	1.0	0	0.640	0.177	0.045	0.073	0.063
13	2.050	15.00	1.30	N/A	1495	2037	1.7	0	0.657	0.182	0.053	0.060	0.044
14	2.287	15.00	1.45	N/A	1561	1945	0.8	0	0.634	0.175	0.043	0.076	0.069

higher than the CARS measurements of Weigand et al. [1] for the eleven conditions considered here. This difference can be attributed to the heat transfer from the flame to the cooled burner body and is directly proportional to the gas velocity (u_{av}). Comparing the uncorrected thermocouple signals with the theoretical values (T_{ad}) shows an average deviation of ~600 K. This difference then drops by half when compared with the CARS measurement of Weigand et al. [1], in good agreement with the observations noted in [6]. A correction of the data to account for the heat loss by the probe through radiation to the cold surrounding would be necessary to reduce this discrepancy with CARS data. The relevant thermocouple properties are provided in the experimental design section.

2. Experimental Design, Materials and Methods

All experiments were carried out using a conventional McKenna flat flame burner (Holthuis & Associates, formerly McKenna Products), consisting of two concentric sintered bronze plugs. The inner plug (38.1 mm OD) provides the fuel/oxidizer mixture to a flame sheet and the outer plug (50.8 mm OD) can be used to generate a shroud flow to shield flames from atmospheric oxygen. Fig. 4 shows the experimental installation. The desired volumetric flow rates for methane, oxygen and nitrogen are maintained through three mass flow controllers (MFC), which are driven by

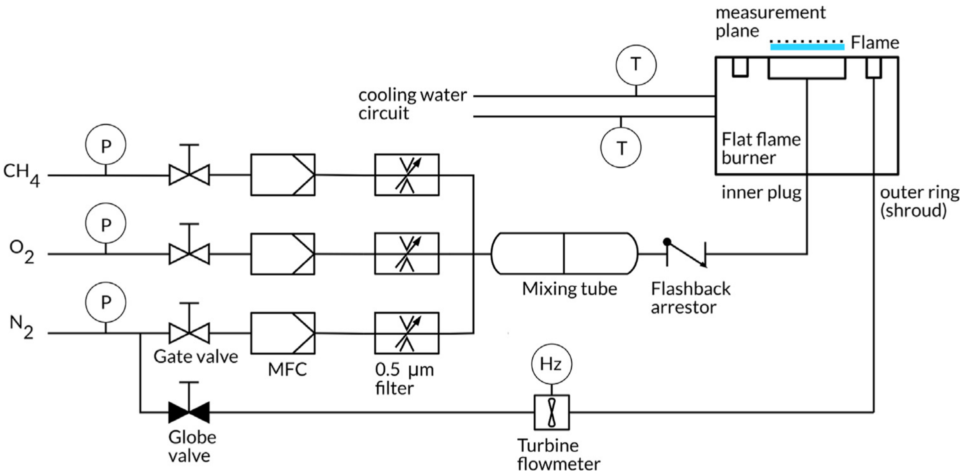

Fig. 4. Schematic representation of the gas handling and connections of the McKenna flat flame burner. All gases except the shroud gas pass through a 0.5 μm filter, then mix before entering the porous sintered inner plug of the burner.

a National Instrument® program. The MFC have been individually calibrated for the appropriate gases using a volumetric primary flow standard (Defender 520, DryCal by Mesa Labs), covering the full range of the instrument (from 0 V to 5 V) in steps of 0.5 V. The accuracy of the mass flow controllers is ±1% of the full range. In the case of methane, the full range is 6.31 slpm, leading to an accuracy of ±0.06 slpm. Consequently, the flames for conditions 9 and 10 are not expected to differ significantly. Instead of compressed air, synthetic air is used by mixing laboratory grade nitrogen and oxygen at fixed molar ratio of 1/3.76. The individual gas streams enter a mixing tube with 21 blades (McMaster-Carr Supply Co. model 3530K51) before being injected into the burner. The mixing tube guarantees homogeneous mixtures over the entire range of Φ. As a safety measure, a flash back arrestor (WITT-Gastechnik GmbH & Co. KG model F53N/H) is installed between the burner and the mixing chamber. The burner is water cooled through an open loop with an average input water temperature of (280.65 ± 2.10) K for all measurement except one. For the thermocouple test series, the input cooling water temperature was significantly higher (300 ± 2.25) K, but we did not expect this differences to induce changes in the flame produced. This temperature is monitored with type T thermocouples (OMEGA Engineering, TQSS-18U-6) and a handheld device (OMEGA Engineering HH509R) with logging function. The temperature fluctuation was not more than ±0.2 K over the entire duration of testing for all test series. The average water flow rate is (4.0 ± 0.5) lpm.

Each test condition was maintained for several minutes prior to initiating the acquisition to ensure steady state boundary conditions and a stable flame. Unless utherwise specified, measurements were taken at a height of 15 mm above the burner plate, a position consistent with the configuration used in the DLR report [1]. At this height and at stoichiometric conditions, combustion can be considered complete and important flame characteristics such as species molar fraction, temperature and gas velocity have reached equilibrium, as can be seen from Fig. 5. For probe-based flame temperature measurements, a small motorized stage moved the thermocouple probe (Fig. 3) in and out the flame. The probe is y-shaped to minimize conduction losses as it is inserted perpendicular to the temperature gradient and the burner plane, thus avoiding perturbing the flow. The bare Type R thermocouple (OMEGA Engineering, P13R-005), was dip-coated with a high-temperature ceramic cement (OMEGA Engineering, Omegabond 600, OB-600), to prevent catalytic effects [7]. The coating thickness was approximately (150 ± 40) microns over the entire exposed range, with the 25% variability attributed to the probe y-shape accumulating more material in the corners.

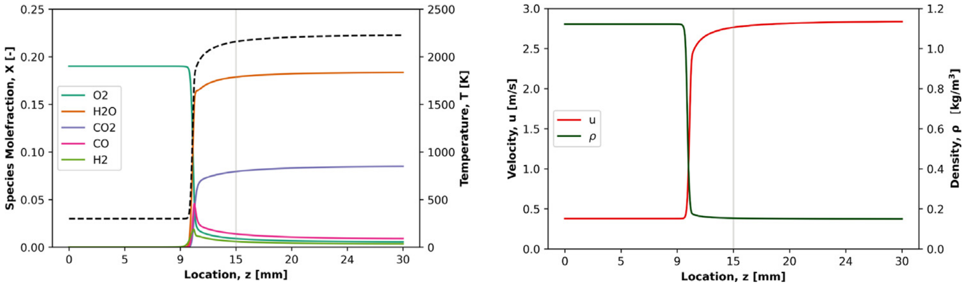

Fig. 5. *Left:* temperature (black dashed line) and mole fraction (colored solid lines) evolution at vertical distance z above the burner plate for stoichiometric methane-air combustion obtained from one-dimensional cantera simulations using the GRI3.0 mechanism [4]. *Right:* velocity and density profiles obtained using the same simulations.

An aluminum flange mounted to the burner main body allows the installation of accessories. A conventional optical post holder (Newport model M-VPH-2) is used to hold the heat flux gauge at the desired height (15 mm above the burner plane) during measurement. The probe is pivoted in and out the flame as needed but kept at the same height and connected to the same water cooling circuit as the burner. The very rich flames associated with conditions 11–14 rise to great heights (150–200 mm) and can potentially damage the heat flux gauge. Consequently, no heat flux density data is reported for these conditions. The different camera systems have been mounted on tripods and camera posts at a fixed position relative to the burner. Individual camera triggering and recording was performed using Photron Fastcam PVF4 software for the Mini AX200 and digiCamControl for the Nikon camera, with both tools being freely available. Telops® Reveal-IR was used for the MS M350 IR camera recording.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

Data Availability

Thermal, optical and chemcial dataset of flat premixed Laminar CH4/air standard flames (Original data) (Mendeley Data).

CRediT Author Statement

Tanja Pelzmann: Investigation, Writing – original draft, Conceptualization, Data curation, Methodology, Formal analysis, Validation, Visualization, Software; **Étienne Robert:** Resources, Writing – review & editing.

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