

The University of Adelaide
School of Chemical Engineering



**Sooting Behaviour of Turbulent
Non-Premixed Jet Flames**

Ph.D. Thesis

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Abstract

Soot measurements using planar laser-induced incandescence (LII) have been performed in three commercial propane-fired flames produced by simple jet (SJ), precessing jet (PJ-P) and bluff-body jet (BB) burners. The flames span a wide range of different global mixing rates for the same nozzle diameter and fuel flow rate. Measurements of their radiation, NO_x emissions and residence times are available. LII has also been performed in a natural gas-fired precessing jet (PJ-NG) flame with the same nozzle diameter and throat Reynolds number as the PJ-P and, in the well characterised “Delft III Flame” from the TNF workshop firing simulated Dutch natural gas.

The PJ-P and the SJ have a similar time-averaged soot volume fraction, \bar{F}_V , which is about an order of magnitude higher than in the BB and about 20 times higher than in the PJ-NG. The integrated total volume of soot, however, in the PJ-P is about 2.5 times higher than in the SJ, 25 times higher than in the PJ-NG and 220 times higher than in the BB. The axial location of the peak, time-averaged soot volume fraction, $\bar{F}_{V,max}$, in the two propane flames issued from a long pipe, the SJ and the BB, are very similar when normalised to the flame length ($x/L_{fl} \approx 0.6$) and consistent with other measurements in simple jet flames. The PJ-P and PJ-NG flames show much closer peaks at $x/L_{fl} \approx 0.37$ and 0.53, respectively, also consistent with the peak heat flux in a precessing jet burner. When normalised to the length of the sooting part, the Delft flame shows a similar location of $\bar{F}_{V,max}$ as the SJ and the BB. The soot in the Delft flame is highly intermittent with \bar{F}_V about 70 times less than in the SJ.

The burnout of soot in the two propane flames issued from a long pipe, the SJ and the BB, and in the natural gas Delft flame, proceeds mainly by increasing intermittency, I , evident by the high instantaneous soot volume fraction, F_V , and the high intermittency in the burnout region. In addition, the soot sheet dimensions do not vary significantly in the burnout region of these flames indicating that burnout proceeds by less number of soot sheets rather than a reduction in their dimensions. The burnout in the PJ-P proceeds by a different mechanism than the other turbulent flames, the asymptotic behaviour of I and the low F_V reveal that the burnout in this flame is mainly due to low soot concentration. The reduction in the size of the soot sheets also indicate that both the dimensions of the sheets and the soot concentration within them drop in the burnout region.

The distribution of the PDF of F_V in the five investigated flames is well characterised by an exponential function, with some departure at low F_V . The axial and radial distributions of the curve fitting parameters $K_{P,F}$ and $K_{P,O}$ of the exponential function for the Delft flame are presented. They were found mostly to vary smoothly with the axial height above the burner. The data provided on the well-defined Delft flame should be of great usefulness for model validation.

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Notation

Abbreviations

BB	Bluff Body
CARS	Coherent anti-Stokes Raman Spectroscopy
CFDF	Counter-Flow Diffusion Flame
CW	Continuous wave
EICO	Emission index of carbon monoxide
EINO _x	Emission index of nitrogen oxides
HeNe	Helium-Neon
JP-8	Jet Propellant 8
ICCD	Intensified Charge-Coupled Device
IR	Infra Red
LDA	Laser Doppler Anemometry
LDV	Laser Doppler Velocimetry
LII	Laser-Induced Incandescence
LIF	Laser-Induced Fluorescence
LPG	Liquified petroleum gas (commercial propane)
MCB	Multi-channel burner
Nd:YAG	Neodymium Yttrium Aluminium Garnet laser
PPB	Parts per billion
PAH	Polycyclic aromatic hydrocarbons
PDF	Probability Density Function
PJ	Precessing Jet
PJ-NG	Precessing Jet-Natural gas
PJ-P	Precessing Jet-propane
PPM	Parts per million
RSD	Relative standard deviation
SJ	Simple jet
TNF	Turbulent Non-Premixed Flames

Roman Symbols

a_0, a_1, a_2, a_3	Curve fitting parameters for the axial distribution of $K_{P,F}$ and $K_{P,O}$
C_{ext}	Power intensity of extinguished laser beam
C_{inc}	Power intensity of incident laser beam
d	Fuel nozzle diameter, PJ chamber inlet diameter
D	Mean soot particle diameter
F_V	Instantaneous soot volume fraction (PPB/PPM)
\bar{F}_V	Time-averaged soot volume fraction (PPB)
F'_V	Integrated soot volume fraction over a line of sight (PPB.mm)
$\bar{F}_{V,Cond}$	Conditional time-averaged soot volume fraction (PPB)
$\bar{F}_{V,Cum}$	Cumulative average of soot volume fraction (PPB)
$F_{V,max}$	Maximum instantaneous soot volume fraction (PPM)
$F^*_{V,max}$	The most probable values of $F_{V,max}$ (PPB)
$\bar{F}_{V,max}$	Maximum time-averaged soot volume fraction (PPB)

$\int \bar{F}_V \cdot dA$	Integrated soot volume fraction over flame cross sectional area (PPM.mm ²)
f_s	Mass fraction of fuel
I	Intermittency of soot
K_e	Dimensionless extinction constant
$K_{P,F}$	Empirical constant of the single exponential distribution function of $P(F_V)$
$K_{P,N}$	Empirical constant of the single exponential distribution function of $P(F_V)$ representing the random noise
$K_{P,O}$	Empirical constant of the single exponential distribution function of $P(F_V)$
L	Soot sheet characteristic length
L'	The longest dimension in the soot sheet evaluated manually
L_{fl}	Flame length
N_{LII}	LII calibration constant (PPB/LII count)
$P(F_V)$	Probability of instantaneous soot volume fraction
$P(F_{V,max})$	Probability of maximum instantaneous soot volume fraction
r	Radial distance from burner axis (mm)
Re	Reynolds number
RSD	Relative standard deviation
S_{LII}	LII signal
S'_{LII}	Integrated LII signal over a line of sight
T	Temperature
T_{fl}	Flame characteristic temperature
u	Fuel exit velocity
u_a	Air exit velocity
W	Soot sheet characteristic width
W'	The longest dimension in the soot sheet along an axis perpendicular to the axis of L' evaluated manually
W_{fl}	Flame width
x	Axial distance above the burner (mm)
Z_{st}	Stoichiometric mixture fraction

Greek Symbols

λ	Wavelength
λ_{Det}	Detection wavelength (microns)
ρ_0	Cold fuel density
ρ_{fl}	Flame density
σ_X	Standard deviation of X
τ_G	Global flame residence time
χ_R	Flame radiant fraction

Statement of originality

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution to Nader H. Qamar and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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