

# **An Experimental Study of Soot Formation in Dual Mode Laminar Wolfhard-Parker Flames**

by

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(ABSTRACT)

An experimental study of sooting characteristics of laminar underventilated ethylene non-premixed flames in hot vitiated environments was performed using a modified Wolfhard-Parker co-flowing slot burner. The burner could be operated in “single mode” with a cold air/oxygen mixture as the oxidizer for the non-premixed flame or in varying degrees of “dual mode” where the products of lean premixed hydrogen/air/oxygen flames were used as the oxidizer for the non-premixed flame. Premixed flame stoichiometries of 0.3 and 0.5 were considered for the dual mode cases. Dual mode operation of the burner was intended to simulate the conditions of fuel rich pockets of gas burning in the wake of previously burned fuel/air mixture as typically found in real nonpremixed combustion devices.

Dual mode operation introduced competing thermal and chemical effects on soot chemistry. Experimental conditions were chosen to match peak nonpremixed flame temperatures among the cases by varying oxidizer inert ( $N_2$ ) concentration to minimize the dual mode thermal effect. In addition the molecular oxygen (post premixed flame for dual mode cases) and ethylene fuel flow rates were held constant to maintain the same overall equivalence ratio from case to case.

Thermocouple thermometry utilizing a rapid insertion technique and radiation corrections yielded the gas temperature field. Soot volume fractions were measured simultaneously with temperature using Thermocouple Particle Densitometry (TPD). Soot volume fraction, particle size and particle number density fields were measured using laser light scattering and extinction. Gas velocities were measured using Particle Imaging Velocimetry (PIV) on the non-premixed flame centerline by seeding the ethylene flow and calculated in the oxidizer flow stream. Porous sinters in the oxidizer slots prevented oxidizer particle seeding required for PIV measurements.

In general as the degree of dual mode operation was increased (i.e. increasing stoichiometry of the premixed flames) soot volume fractions decreased, particle sizes increased and soot particle number densities decreased. This trend is suspected to be result of water vapor elevating OH concentrations near the flame front in dual mode operation reducing soot particle nucleation early in the flame by oxidizing soot precursors. The larger particle sizes measured at later stages of dual mode flames are suspected to be the result of lower competition for surface growth species for the lower particle number densities in those flames. Integrated soot volume fraction and particle number fluxes at various heights in the flame decreased with increasing degree of dual mode operation.

# Table of Contents

<b>1.0 Introduction .....</b>	<b>1</b>
1.1 Background.....	1
1.2 Objective.....	3
<b>2.0 Literature Review and Approach .....</b>	<b>4</b>
2.1 Overview of Soot Formation in Flames.....	4
2.1.1 Soot Particle Evolution .....	4
2.1.2 Parameters Affecting Soot Formation in Flames.....	6
2.1.2.1 Temperature .....	6
2.1.2.2 Oxygen Addition to Nonpremixed Flame Fuel.....	8
2.1.2.3 Varying Nonpremixed Flame Oxidizer Oxygen Index.....	8
2.1.2.4 Radical Diffusion in Nonpremixed Flames.....	9
2.1.3 Previous Studies on Dual Mode Combustion .....	10
2.2 Approach Chosen for the Present Study .....	14
2.2.1 Survey of Wolfhard-Parker Laminar Nonpremixed Flame Studies ...	15
2.2.2 Measurement Techniques .....	20

<b>3.0 Experimental Apparatus and Methods.....</b>	<b>21</b>
3.1 Dual Mode Wolfhard-Parker Burner.....	21
3.2 Gas Supply and Metering .....	26
3.3 Computer A/D Board and Stepper Motor Linear Stages.....	27
3.4 Temperature Measurement .....	28
3.4.1 Thermocouple Construction and Preparation .....	28
3.4.2 Implementation of Rapid Insertion Thermocouple Thermometry..... and Thermocouple Particle Densitometry (TPD)	31
3.5 Laser Light Scattering and Extinction.....	38
3.5.1 Scattering and Extinction Optical Train .....	38
3.5.2 Interaction of Light with Particles.....	42
3.5.3 Extinction Measurement and Analysis.....	44
3.5.4 Scattering Measurement and Analysis .....	45
3.6 Velocity .....	48
3.6.1 Particle Imaging Velocimetry.....	48
3.6.2 Velocity Calculations.....	51
 <b>4.0 Experimental Conditions and Burner Operation.....</b>	 <b>56</b>
4.1 Experimental Conditions .....	56
4.2 Burner Operating Procedures .....	59
4.2.1 Cooling Water.....	59
4.2.2 Lighting the Burner .....	60
4.2.3 Stabilizing the Flame.....	60
4.2.4 Burner Operation Notes .....	61

4.2.5 Burner Shutdown .....	62
<b>5.0 Results and Discussion.....</b>	<b>63</b>
5.1 Temperature.....	63
5.2 Thermocouple Particle Densitometry Soot Volume Fraction.....	73
5.3 Laser Light Scattering and Extinction.....	76
5.3.1 Laser Light Extinction (LLE) .....	76
5.3.2 Laser Light Scattering (LLS) Soot Particle Diameters.....	83
5.3.3 Laser Light Scattering (LLS) Soot Particle Number Density .....	87
5.4 Velocity Measurements and Calculations.....	91
5.5 Flux Calculations.....	96
5.6 Interpretation .....	98
<b>6.0 Conclusions and Recommendations.....</b>	<b>101</b>
6.1 Summary and Conclusions.....	101
6.2 Recommendations for Future Work.....	103
<b>References .....</b>	<b>105</b>

<b>Appendix A Application of Thermocouples in Steady Laminar Flames .....</b>	<b>111</b>
A.1 Thermocouple Thermal Capacitance .....	111
A.2 Thermocouple Thermometry in Non-Sooting Flames .....	113
A.3 Thermocouple Thermometry in Sooting Flames .....	116
A.4 Thermocouple Particle Densitometry .....	119
A.5 Convection Heat Transfer Properties of Thermocouple Junctions.....	123
<b>Appendix B Burner Mechanical Drawings.....</b>	<b>133</b>
<b>Appendix C Rotameter Calibrations .....</b>	<b>143</b>
<b>Appendix D Uncertainty Analysis.....</b>	<b>149</b>
D.1 Measurement Uncertainty .....	149
D.2 Thermocouple Convection Properties Uncertainty .....	151
D.3 Gas Temperature Uncertainty .....	154
D.4 Extinction Soot Volume Fraction Uncertainty.....	156
<b>Vita .....</b>	<b>158</b>

## List of Figures

Figure 3.1	Wolfhard-Parker Burner Schematic .....	22
Figure 3.2	Burner / Base Assembly .....	23
Figure 3.3	Ceramic Honeycomb Flow Conditioning .....	24
Figure 3.4	Burner Cross Section .....	25
Figure 3.5	Burner Enclosure Assembly .....	26
Figure 3.6	DT2805 A/D Board Calibration Results .....	28
Figure 3.7	Thermocouple Construction Schematic .....	30
Figure 3.8	Typical Thermocouple Junction .....	31
Figure 3.9	Thermocouple Time Constant, $\tau$ , Determination .....	34
Figure 3.10	Thermocouple Temperature Versus Time in a Sooting Region .....	36
Figure 3.11	Scattering and Extinction Optical Train .....	39
Figure 3.12	Beam Extinction Correction for Scattering Analysis .....	47
Figure 3.13	Schematic of Particle Imaging Velocimetry Facility .....	49
Figure 3.14	Single Mode Flame Flow Seeding .....	50
Figure 3.15	Velocity Model Grid Scheme .....	53

Figure 4.1	Wolfhard-Parker Flames.....	58
Figure 5.1	Corrected Temperature Fields .....	64
Figure 5.2	Temperature Correction Magnitudes .....	65
Figure 5.3	Maximum and Centerline Temperatures.....	66
Figure 5.4	Transverse Temperature Profiles, Height 1mm .....	68
Figure 5.5	Corrected Gas Temperature Profiles at Various Heights .....	69
Figure 5.6	Gas Temperature Uncertainty Versus Gas Temperature.....	70
Figure 5.7	Thermocouple Output Voltage as Flame Extinguishes .....	70
Figure 5.8	Transverse Temperature Gradients at Various Heights .....	72
Figure 5.9	TPD Soot Volume Fractions (linear color map) with Isotherms .....	74
Figure 5.10	TPD Soot Volume Fractions (log color map) with Isotherms.....	75
Figure 5.11	Laser Extinction Soot Volume Fraction (linear color map) .....	77
Figure 5.12	Laser Extinction Soot Volume Fraction (log color map).....	78
Figure 5.13	LLE Soot Volume Fraction Profiles at Various Heights.....	79
Figure 5.14	Soot Volume Fraction Uncertainty vs. Soot Volume Fraction.....	80
Figure 5.15	Soot Volume Fraction Peak Values vs. Height.....	82
Figure 5.16	Light Scattering Measurements of Soot Particle Diameter ( $D_{63}$ ) .....	85
Figure 5.17	LLS Soot Particle Diameters ( $D_{63}$ ) at Various Heights.....	86
Figure 5.18	LLS Peak Soot Particle Diameters ( $D_{63}$ ) vs. Height .....	87
Figure 5.19	Laser Light Scattering Soot Particle Number Densities.....	88
Figure 5.20	LLS Soot Particle Number Densities at Various Heights.....	89
Figure 5.21	LLS Peak Soot Particle Number Densities vs. Height .....	90

Figure 5.22	Domain of Seeded Flow for PIV Measurements .....	92
Figure 5.23	Unseeded Oxidizer Region Width for Velocity Calculations.....	93
Figure 5.24	Measured and Calculated Centerline Vertical Velocities.....	94
Figure 5.25	Calculated Vertical Velocities.....	95
Figure 5.26	Integrated Soot Volume Fraction Flux { $\text{cm}^2 \text{s}^{-1}$ }.....	97
Figure 5.27	Integrated Soot Particle Number Density Flux {particles $\text{cm}^{-1} \text{s}^{-1}$ } .....	97
Figure 5.28	Flame Front Temperatures and Equilibrium Hydroxyl Concentrations.....	100
Figure A.1	First Order System Step Response.....	112
Figure A.2	Thermocouple Time Trace in a Sooting Flame [McEnally <i>et al.</i> , 1997] ...	118
Figure A.3	G(t) Transformation of T(t) [McEnally <i>et al.</i> , 1997].....	122
Figure A.4	Nusselt Numbers for Infinite Cylinders and Spheres vs. Reynolds .....	125
	Number	
Figure A.5	Thermocouple Radiation Corrections for Cylindrical and Spherical .....	125
	Junction Convection Models	
Figure A.6	TPD Soot Volume Fraction Sensitivity to Junction Nusselt Number .....	126
Figure A.7	Schematic representation of a typical thermocouple junction .....	127
	relative to cylindrical and spherical idealisms	
Figure A.8	Assumed Spherical Reference Thermocouple Junction, 50 $\mu\text{m}$ wire, .....	128
	$d_j / d_w = 8.8$	
Figure A.9	Thermocouple Junction Image for Sample Calculation, 50 $\mu\text{m}$ wire, .....	130
	$d_j / d_w = 3.8$	
Figure A.10	Normalized Thermocouple Junction Nusselt Number Measurements.....	132
	vs. Nondimensionalized Junction Diameter, all 50 $\mu\text{m}$ Wire	

Figure B.1	Burner North and South Walls, Drawing 2 Sheet 1 of 2.....	134
Figure B.2	Burner North and South Walls, Drawing 2 Sheet 2 of 2.....	134
Figure B.3	Burner Slot Dividing Walls, Drawing 3 Sheet 1 of 1 .....	125
Figure B.4	Burner Mounting Base, Drawing 4 Sheet 1 of 5.....	136
Figure B.5	Burner Mounting Base, Drawing 4 Sheet 2 of 5.....	136
Figure B.6	Burner Mounting Base, Drawing 4 Sheet 3 of 5.....	137
Figure B.7	Burner Mounting Base, Drawing 4 Sheet 4 of 5.....	137
Figure B.8	Burner Mounting Base, Drawing 4 Sheet 5 of 5.....	138
Figure B.9	Burner Mounting Base Gasket, Drawing 6 Sheet 1 of 2.....	139
Figure B.10	Burner Gas Inlet Manifold Gasket, Drawing 6 Sheet 2 of 2.....	139
Figure B.11	Burner Gas Inlet Manifold, Drawing 7 Sheet 1 of 1 .....	140
Figure B.12	Burner Surround East and West Walls, Drawing 8 Sheet 1 of 2 .....	141
Figure B.13	Burner Surround East and West Walls, Drawing 8 Sheet 2 of 2 .....	141
Figure B.14	Burner Surround North and South Walls, Drawing 9 Sheet 1 of 2 .....	142
Figure B.15	Burner Surround North and South Walls, Drawing 9 Sheet 2 of 2 .....	142
Figure C.1	Air Rotameter Calibration Curve .....	144
Figure C.2	Oxygen Rotameter Calibration Curve .....	145
Figure C.3	Hydrogen Rotameter Calibration Curve.....	146
Figure C.4	Ethylene Rotameter Calibration Curve.....	147
Figure C.5	Nitrogen Rotameter Calibration Curve .....	148

## List of Tables

Table 4.1	Oxidizer Slot Flow Conditions.....	57
Table 5.1	Oxidizer Mole Fraction Composition.....	99
Table A.1	Values of n, A and B for Equation A.21 .....	123

## Nomenclature

$c$	specific heat	$L$	optical extinction path-length
$d$	diameter, depth	$I$	light intensity
$f_v$	soot volume fraction	$MW$	molecular weight
$h$	heat transfer coefficient	$N$	number density
$j''$	mass flux	$Q$	volumetric scattering cross section
$k_{ext}$	optical extinction coefficient	$R_u$	universal gas constant
$\tilde{m}$	complex index of refraction	$S$	lock-in amplifier gain
$\dot{m}$	mass flow	$S_x$	standard deviation
$p$	pressure	$T$	temperature
$t$	time	$V$	voltage, volume
$v$	velocity		
$w$	width		
$\bar{x}$	average		
$A$	area		
$C$	differential scattering cross section		
$D$	diameter		
$D_T$	thermophoretic diffusivity		

$\alpha$	momentum accommodation coefficient
$\varepsilon$	radiant emissivity
$\phi$	soot volume fraction
$\varphi$	soot deposit density ratio
$\eta$	normalized thermocouple Nusselt number ratio
$\lambda$	wavelength
$\mu$	dynamic viscosity
$\nu$	kinematic viscosity
$\theta$	angle
$\rho$	density
$\rho_p$	intrinsic soot density
$\rho_D$	soot deposit density
$\sigma$	Boltzman's constant
$\zeta$	mixture fraction
$\tau$	time constant
$\Psi$	integrated flux

## Subscripts

0	incident
63	sixth to third statistical moment ratio
atm	atmospheric
d	based on diameter
cal	calibration
cyl	cylindrical
exp	experiment
i	index
j	index
ref	reference
rel	relative to reference
s	surface
sph	sphere
tc	thermocouple
$\infty$	infinity

## Abbreviations and Acronyms

A / D	analog to digital
LLE	laser light extinction
LLS	laser light scattering
NIST	National Institute of Standards and Technology
Nu	Nusselt number
OD	outer diameter
PAH	Polycyclic Aromatic Hydrocarbons
PIV	particle imaging velocimetry
PMT	photomultiplier tube
Pr	Prandtl number
Re	Reynolds number
STP	standard temperature and pressure
TC	thermocouple
TPD	thermocouple particle densitometry

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