

University of Groningen

## Laser Diagnostics of Combustion-Generated Nanoparticles

Langenkamp, Peter Niek

**IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.**

*Document Version*

Publisher's PDF, also known as Version of record

*Publication date:*

2018

[Link to publication in University of Groningen/UMCG research database](#)

*Citation for published version (APA):*

Langenkamp, P. N. (2018). *Laser Diagnostics of Combustion-Generated Nanoparticles*. Rijksuniversiteit Groningen.

### Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

### Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.



rijksuniversiteit  
 groningen

# Laser diagnostics of combustion-generated nanoparticles

## **Proefschrift**

ter verkrijging van de graad van doctor aan de  
 Rijksuniversiteit Groningen  
 op gezag van de  
 rector magnificus prof. dr. E. Sterken  
 en volgens besluit van het College voor Promoties.

De openbare verdediging zal plaatsvinden op  
 vrijdag 21 december 2018 om 11:00 uur

door

**Peter Niek Langenkamp**

geboren op 7 oktober 1989  
 te Anloo

**Promotor**

Prof. dr. H.B. Levinsky

**Copromotor**

Dr. A.V. Mokhov

**Beoordelingscommissie**

Prof. dr. ir. H.J. Heeres

Prof. dr. D.J.E.M. Roekaerts

Prof. dr. ir. T.H. van der Meer

ISBN: 978-94-034-1219-1 (Print)

978-94-034-1218-4 (Electronic)

---

## Contents

<b>Chapter 1. Introduction .....</b>	<b>1</b>
1.1. Combustion-generated particles.....	2
1.2. Fractal aggregates.....	2
1.2.1. Aggregate structure.....	3
1.2.2. Time dependence of aggregate radius .....	5
1.3. Particle species.....	8
1.3.1. Soot.....	8
1.3.2. Silica .....	9
1.4. Scope and outline of this thesis.....	11
References .....	13
<b>Chapter 2. Flames and gas burners .....</b>	<b>15</b>
2.1. Introduction .....	16
2.2. Flat Laminar Premixed Burner-Stabilized Flames .....	17
2.3. Calculating the structure of flat laminar premixed flames .....	19
2.3.1. Overall conservation of mass.....	19
2.3.2. Conservation of species mass .....	20
2.3.3. Conservation of energy.....	21
2.3.4. Ideal gas equation of state .....	21

2.3.5. Boundary conditions .....	21
2.4. Gas burners.....	22
2.4.1. McKenna Flat Flame Burner .....	22
2.4.2. Home-made burner .....	23
2.5. Gas handling system.....	24
2.6. Siloxane addition through bubbler system .....	25
References .....	27
<b>Chapter 3. Diagnostic methods &amp; experimental setups .....</b>	<b>29</b>
3.1. Introduction .....	30
3.2. Angle-dependent light scattering (ADLS) .....	31
3.2.1. Theory.....	31
3.2.2. Setup.....	34
3.3. Laser light extinction (LLE) .....	36
3.4. Laser-induced incandescence (LII) .....	37
3.4.1. Setup and measurements .....	38
3.5. Raman spectroscopy.....	39
3.5.1. Setup.....	40
3.5.2. Measurement procedure .....	41
References .....	43
<b>Chapter 4. Silica aggregate growth in 1-D methane/air flames .....</b>	<b>47</b>
4.1. Introduction .....	48
4.2. Experimental .....	49
4.3. Dependence of aggregate size on Si concentration.....	50
4.4. Temperature dependence.....	55
4.5. Dependence of aggregate growth on equivalence ratio.....	57
4.6. Summary and conclusions .....	58
References .....	59

<b>Chapter 5. Effects of hydrogen addition on silica aggregate growth.....</b>	<b>63</b>
5.1. Introduction .....	64
5.2. Experimental .....	64
5.3. Results and discussion.....	65
5.3.1. Dependence of aggregate size on hydrogen fraction.....	67
5.3.2. Monomer size .....	69
5.3.3. Effect of equivalence ratio .....	71
5.4. Conclusions .....	72
Appendix 5.A.....	74
References .....	79
<b>Chapter 6. Soot aggregate growth in 1-D ethylene/air flames .....</b>	<b>83</b>
6.1. Introduction .....	84
6.2. Experimental .....	85
6.2.1. Burner system and gas supply .....	85
6.2.2. Raman temperature measurements.....	86
6.2.3. Soot measurements .....	87
6.3. Flame modeling.....	88
6.4. Results and discussion.....	89
6.4.1. Temperature measurements .....	89
6.4.2. Soot volume fraction measurements .....	91
6.4.3. Aggregate size measurements.....	95
6.5. Conclusions .....	98
References .....	100
<b>Chapter 7. Effects of hydrogen addition on soot aggregate growth .....</b>	<b>103</b>
7.1. Introduction .....	104
7.2. Experimental .....	105
7.3. Results and discussion.....	106

7.3.1. Soot volume fraction measurements.....	108
7.3.2. Aggregate size measurements.....	109
7.3.3. Monomer size.....	110
7.4. Conclusions.....	111
References.....	113
<b>Summary.....</b>	<b>115</b>
<b>Samenvatting.....</b>	<b>119</b>
<b>Acknowledgments.....</b>	<b>123</b>