Available online at www.sciencedirect.com

SCIENCE DIRECT®

International Journal of Heat and Mass Transfer 47 (2004) 5381–5385

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Technical Note

An experimental investigation of sootshell formation in microgravity droplet combustion

Samuel L. Manzello [a,*], Ahmet Yozgatligil [b], Mun Young Choi [b]

[a] *Building and Fire Research Laboratory, National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899-8662, USA*
[b] *Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, PA 19014, USA*

Received 9 February 2004; received in revised form 2 July 2004

Abstract

Spherically symmetric droplet combustion experiments were performed at the NASA Glenn Research Center (GRC) 2.2 second drop tower in Cleveland, OH in an effort to better understand the mechanism leading to sootshell formation. Rapid insertion of a blunt plunger was used to remove the symmetric sootshell that formed during the period of quasi-steady burning. This allowed for the observation of sootshell re-formation. Soot particles were formed near the flame front and migrated towards the droplet to ultimately reside at the sootshell location. These experiments helped to bring about a better understanding of soot transport in microgravity droplet combustion.

Keywords: Microgravity combustion; Droplet Burning; Soot

---

1. Introduction

Spherically symmetric droplet combustion studies can be used to develop and validate sub-models that can be incorporated into more complex models of spray processes [1–4]. Generating spherically symmetric flames requires the use of a microgravity environment to eliminate buoyant transport. Single droplet combustion studies performed in microgravity can be used as a first step for advancing understanding of complex spray processes [1–4].

An important observation, which the present study is predicated on, was the formation of a spherically symmetric sootshell between the droplet surface and the flame front. The formation of the sootshell, unique in microgravity, is thought to influence the droplet burning process in ways not previously considered. [5,6]. To elucidate the influence of sooting on droplet burning requires detailed understanding of sootshell formation.

The formation of a spherically symmetric sootshell was first reported by Shaw et al. [7]. Choi et al. [8] and Jackson and Avedisian [9] modeled the spherically symmetric combustion of an *n*-heptane droplet. The sootshell location was defined where the Stefan and thermophoretic velocities (or fluxes) counter-balanced. Both models over-predicted the location of the sootshell. Perea et al. [10] developed a model to describe the gas-phase temperature distribution around a droplet. The sootshell location was defined where the particle velocity was equal to zero. It was concluded that thermophoresis and drag alone cannot explain sootshell formation.

---

[*] Corresponding author. Tel.: +1 301 975 6891; fax: +1 301 975 4052.
E-mail address: samuel.manzello@nist.gov (S.L. Manzello).

0017-9310/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2004.07.008

Nomenclature

D	mass diffusivity
FSR	flame standoff ratio (flame diameter divided by droplet diameter)
f_v	soot volume fraction
Le	Lewis Number, $Le = \alpha/D$
m	complex index of refraction
r	radius
SSR	soot standoff ratio (sootshell diameter divided by droplet diameter)
v	velocity

Greek symbol

α	thermal diffusivity

Subscripts

i	instantaneous
ph	photophoresis
th	thermophoresis

Perea et al. [10] subsequently modified their model by incorporating photophoresis and the sootshell was predicted to be stable at a SSR ~ 4.3. Recently, Ben-Dor et al. [11] performed numerical analysis on the formation of sootshell structure in buoyancy-free spherical *n*-heptane droplet flames. It was concluded that the effect of the diffusiophoretic force was significant and must be included to explain sootshell formation [11]. Dobbins et al. [12] suggested an *alternative* mechanism for the formation of sootshells. They reported that the particles within the sootshell may initially be comprised primarily of soot precursor material and the carbonaceous particles are then formed through carbonization of the condensed soot precursor material at the sootshell location.

Based upon the different modeling results, differences exist regarding the mechanism of sootshell formation. Experimental observation of sootshell formation tends to be difficult to achieve in practice. In droplet combustion, sootshells are formed within 0.1 s after ignition. At such short times after ignition, sootshell formation occurs in the midst of a dynamic environment in which the flame size and the attendant gradients in temperature are changing. In the present study, observation of the sootshell formation process in microgravity droplet combustion is presented. An experimental technique is described that allowed the sootshell to be displaced after it has formed. During the re-formation process, the flame size remained nearly constant, thus eliminating the difficulties described above. These experiments helped to bring about a better understanding of soot transport in microgravity droplet combustion.

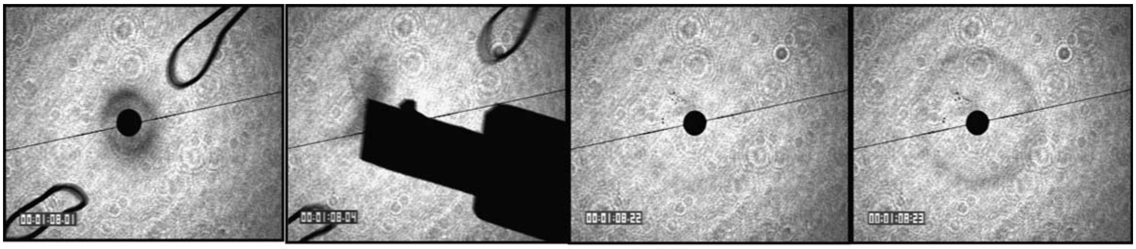
2. Experimental description

Experiments were performed at the NASA-GRC 2.2 second drop tower. The details of the experimental apparatus are given elsewhere [13]. For this reason, only a brief description will be provided here. During the microgravity experiments, a stepper motor driven syringe was used to generate the fuel droplets onto a 15 μm diameter SiC fiber. The liquid fuel droplet was ignited using two horizontally opposed hot-wire igniters. Droplet diameter was measured by digitizing the laser backlit image of the droplet as a function of time and applying a non-subjective image processing technique to threshold the droplet from the background. The luminous droplet flames were imaged using a high-resolution CCD camera and the flame diameter was determined by measuring the spatial extent of the luminous region. Soot volume fraction distributions were obtained by applying a three-point Abel inversion to the projected light extinction measurements [6].

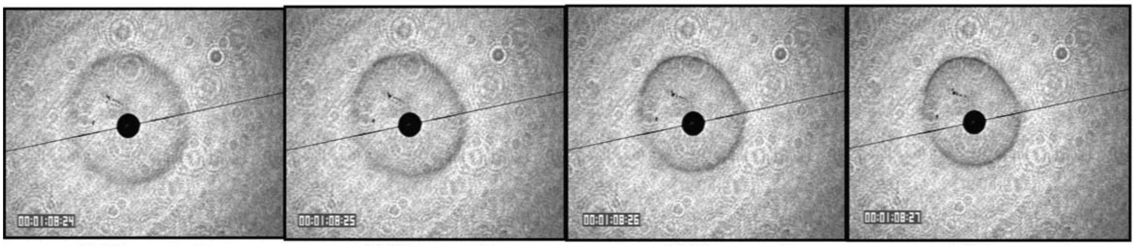
In order to displace the sootshell and cause re-formation, a pneumatic probe was inserted and retracted rapidly into the droplet flame. The velocity of the sampling probe during sootshell displacement was 30 cm/s. This value was the same for both insertion and retraction. The probe insertion speed was varied to determine conditions to effectively displace the sootshell. If the probe velocity was too low, the sootshell remained in place. The total residence time of the probe within the flame (defined as time probe initially reached the luminous flame boundary to the time the probe was retracted from the luminous flame boundary) was 0.5 s.

3. Results and discussion

Fig. 1 displays laser backlit images for a hexane droplet of 1.44 mm in initial diameter burning under microgravity conditions. Soot volume fraction was calculated as a function of time after sootshell displacement. The relative standard uncertainty in measuring soot volume fraction was ±15%. Plotted in Fig. 2 is the spatial variation of the soot volume fraction as a function of time. The maximum soot volume fraction increased as the sootshell migrated towards the droplet surface. The increase in soot volume fraction may be an artifact of constraining the same amount of soot to a smaller volume. To gauge the total sooting magnitude required measurement of the soot mass. The soot mass



Before Displacement **Displacement** **0.09 seconds** **0.12 seconds**



0.15 seconds **0.18 seconds** **0.21 seconds** **0.24 seconds**

Fig. 1. Laser backlit images for a hexane droplet of 1.44mm in initial diameter burning under microgravity conditions. Sootshell displacement and re-formation are shown.

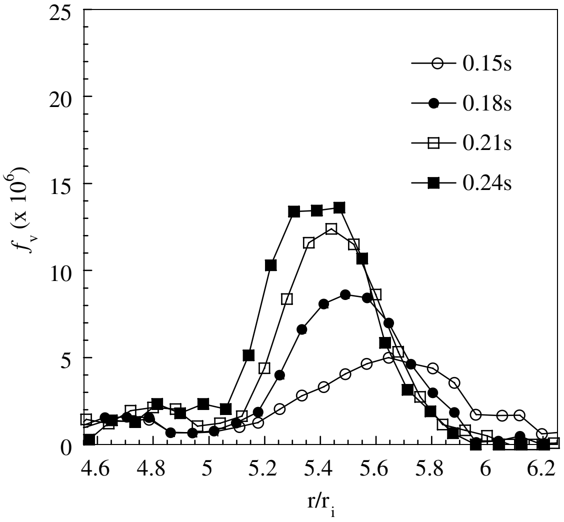


Fig. 2. Soot volume fraction distribution as a function of non-dimensionalized radial position. For each distribution time was defined as the time after sootshell displacement.

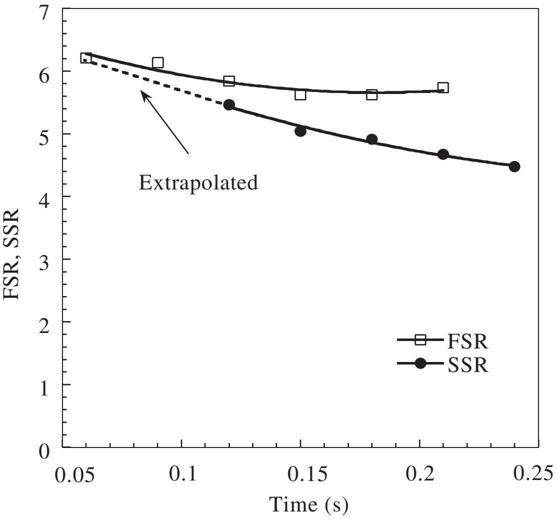


Fig. 3. FSR and SSR as a function of time after sootshell displacement.

was calculated by integrating the soot volume fraction distribution with respect to the volume of the soot containing region. The calculated soot mass increased (due to soot formation and growth) as the sootshell migrated radially inward. Therefore, the increase in soot volume fraction cannot be due solely to compression of the same amount soot into a smaller volume.

The FSR and SSR were determined as a function of time after sootshell displacement and are shown in Fig. 3. The uncertainty in these measurements was ±5%. The FSR remained nearly constant during the observation period which suggests the presence of quasi-steady conditions. However, the SSR decreased markedly as time progressed. More significantly, the magnitude of the FSR and SSR were nearly equal at the time of sootshell re-formation. This suggests that soot particles were formed near the high-temperature region and subsequently transported in the direction of the droplet.

Plotted in Fig. 4 is the average sootshell velocity versus radial location. The maximum velocity of the sootshell was located near the flame front. The velocity of

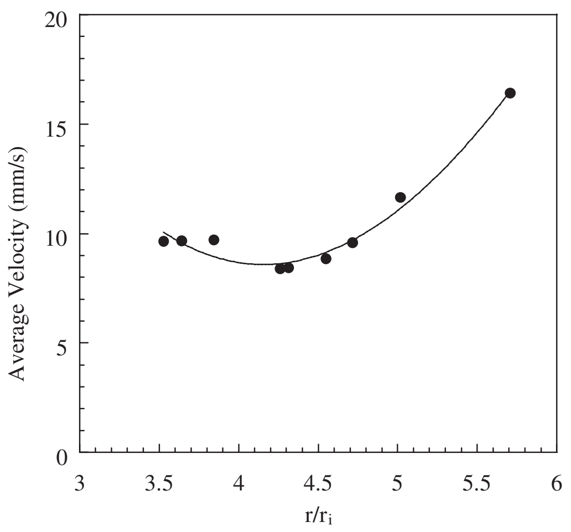


Fig. 4. Sootshell velocity as a function of non-dimensional radial position.

the sootshell decreased as the sootshell moved towards the droplet surface. The reduction in sootshell velocity was speculated to be due to the increase in viscous drag.

The model of Perea et al. [10] suggested that photophoresis was a necessary component in forming a stable sootshell. Mackowski [14] analyzed the influence of photophoretic velocity in combustion systems and defined the ratio of the photophoretic Lewis number to that of the thermophoretic Lewis number as

$$\frac{Le_{\mathrm{ph}}}{Le_{\mathrm{th}}} \propto \frac{v_{\mathrm{ph}}}{v_{\mathrm{th}}} \tag{1}$$

This ratio was dependent on the size as well as the complex refractive index of the particles. The complex index of refraction typically used for soot ($m = 1.57 - 0.56i$) and soot particle size in microgravity droplet combustion [15] was used to interpolate the results of Mackowski [14]. Based on this interpolation, the ratio of $v_{\mathrm{ph}}/v_{\mathrm{th}}$ was $\approx$0.01. Thus, for soot particles, the magnitude of the photophoretic velocity was expected to be $\sim$1% of the thermophoretic velocity.

4. Conclusions

Experimental observation of the mechanism of sootshell formation, from initiation near the flame and transport of the soot toward the sootshell, was presented. Soot particles were formed near the flame front and migrated towards the droplet under the influence of thermophoresis. The sootshell velocity decreased as it moved towards the droplet surface. The reduction in sootshell velocity was due to an increase in viscous drag due to the Stefan flux. Photophoresis is not believed to be an important mechanism in the transport of soot agglomerates.

Acknowledgments

We acknowledge the insights and helpful discussions provided by Dr. Paul Ferkul of the NASA Glenn Research Center. The support of the NASA-GRC staff is sincerely appreciated. This work was supported by NASA through Grant NCC3-822.

References

[1] G.M. Faeth, Current status of droplet and liquid combustion, Prog. Energy Combust. Sci. 3 (1977) 191–224.

[2] F.A. Williams, Droplet burning, in: T.H. Cochran (Eds.), Combustion Experiments in Zero-Gravity Laboratory, Progress in Astronautics and Aeronautics 73 (1981) 31–48.

[3] C.K. Law, Recent Advances in droplet vaporization and combustion, Prog. Energy Combust. Sci. 8 (1982) 171–201.

[4] C.K Law, G.M Faeth, Opportunities and challenges of combustion in microgravity, Prog. Energy Combust. Sci. 20 (1994) 65–113.

[5] G.S. Jackson, C.T. Avedisian, J.C. Yang, Observations of soot during droplet combustion at low gravity: Heptane and heptane/monochloroalkane mixtures, Int. J. Heat Mass Transfer 35 (8) (1992) 2017–2033.

[6] S.L. Manzello, M.Y. Choi, A. Kazakov, F.L. Dryer, R. Dobashi, T. Hirano, The burning of large *n*-heptane droplets in microgravity, Proc. Combust. Inst. 28 (2000) 1079–1086.

[7] B.D. Shaw, F.L. Dryer, F.A. Williams, J.B. Haggard Jr., Sooting and disruption in spherically-symmetrical combustion of decane in air, Acta Astronautica 17 (1988) 1195–1202.

[8] M.Y. Choi, F.L. Dryer, G.J. Green, J.J. Sangiovanni, Soot Agglomeration in Isolated, Free Droplet Combustion, AIAA Paper 93-0823, 1993.

[9] G.S. Jackson, C.T. Avedisian, Modeling of spherically symmetric droplet flames including complex chemistry: Effect of water addition on *n*-heptane droplet combustion, Combust. Sci. Tech. 115 (1996) 125–149.

[10] A. Perea, P.L. Garcia-Ybarra, J.L. Castillo, Soot diffusive transport effects affecting soot shell formation in droplet combustion, Proc. Mediterranean Combust. Symp., 1999.

[11] G. Ben-Dor, T. Elperin, B. Krasovitov, Effect of thermo- and diffusiophoretic forces on the motion of flame-generated particles in the neighbourhood of burning droplets in microgravity conditions, P. Roy. Soc. Lond. A 459 (2003) 677–703.

[12] R.A. Dobbins, G.J. Govatzidakis, W. Lu, A.F. Schwartzman, R.A. Fletcher, Carbonization rate of soot precursor particles, Combust. Sci. Tech. 121 (1996) 103–121.

[13] S.L. Manzello, Microgravity droplet combustion: an experimental investigation on the influence of sooting and radiation on droplet burning, PhD thesis, University of Illinois, Chicago, IL, 2000.

[14] D.W. Mackowski, Photophoresis of aerosol particles in the free molecular and slip-flow regimes, Int. J. Heat Mass Transfer 32 (1989) 843–854.

[15] S.L. Manzello, M.Y. Choi, Morphology of soot collected in microgravity droplet flames, Int. J. Heat Mass Transfer 45 (5) (2002) 1109–1116.