Proceedings of the 10th Brazilian Congress of Thermal Sciences and Engineering – ENCIT 2004
Federal University of Rio de Janeiro, Brazil, Nov. 29 – Dec. 03, 2004
Invited Lecture

Paper CIT04-IL17

INTERACTIVE EFFECTS DURING DROPLET-STREAM VAPORIZATION AND COMBUSTION

Albino J.K. Leiroz
Department of Mechanical Engineering
Federal University of Rio de Janeiro
P.O. Box 68503, 21945-970 Rio de Janeiro - RJ - Brazil
leiroz@ufrj.br

Aldélio B. Caldeira
Department of Mechanical Engineering and Materials Science
Military Institute of Engineering
Praça General Tiburcio, 80, 22290-270, Rio de Janeiro - RJ - Brazil
aldelio@ime.eb.br

Abstract. *A literature review on droplet interaction effects duringvaporization and combustion of fuels under subcriticalconditions is presented in the current work situating differentaspects of the phenomena. Although focused multi-dropletsworks, the review also encompasses some isolated dropletsstudies for completeness of discussion. It is stressed that thesmall and large scales the phenomena impose limiting a factorfor experimental, theoretical or pure numerical approaches.*

keywords: *Vaporization, Combustion, Sprays, Droplets*

1. Introduction

Combustion processes have been intrinsically connected to the development of human society. From the early needs for heating, cooking and metal working, this almost symbiotic relationship evolved into a modern-era Engineering task with important and interconnected technical, economical and environmental facets.

Solid fuels, in the form of coal and wood, were used extensively in combustion devices until the first half of the nineteenth century. Air pollution problems and low thermal efficiency for the available equipment are among solid fuel characteristics which tarnish their general use. Also, the discovery and commercial exploration of petroleum and gas resources reduced the solid fuels contribution to the energetic matrix. Liquid and gaseous fuels bring the advantages of easy handling, low cost and high equipment efficiency. In particular, liquid fuels allow more composition options to be explored during the refining process (Bartok and Sarofim, 1991). The realization that the fuels on which modern society is deeply dependent on are a limited resource brings to Engineers not only the task of searching for alternative sources of energy, but also of improving the utilization of the present resources.

This scenario of fuel utilization on combustion processes have economical implications. Imported-oil dependent nations realized their weakness during and after the Oil Crisis (1973) and other political storms which are frequent to most of the production countries. Petroleum reserves before economically inviable became attractive, requiring, in some cases, the development of new exploration technologies. As the demand for liquid and gaseous fuels approach the production level of petroleum and natural gas, experts predict an increase of solid fuel demand for conversion processes (Bartok and Sarofim, 1991, Chiger, 1981) . Besides the demand for efficiency imposed by a globalized economy leads to a quest for improved design of industrial installation and individual equipments which were previously neglected in front of once more significant costs.

Combustion is one of the major sources of air pollution and technological advances can bring significant improvements in this area. In highly populated areas, automotive and industrial emissions lead to significant smog problems and the introduction of legislation to reduce and control the problem. Design considerations regarding temperature, mixing and residence time should be considered in order to reduce the emission of combustible products associated with incomplete reaction. Carbon dioxide (CO_2) and nitrogen products (NO, NO_2, N_2O) are also considered as pollutants due to their connection to the Greenhouse Effect and acid rain phenomena, respectively. While carbon dioxide emission can be reduced by the use of fuels with high-energy release to carbon content ratio, nitrogen-products emission control can be achieved by the use of low burning temperatures and fuel rich mixtures. It is noteworthy mentioning that these nitrogen-products emission control methodology naturally leads to low combustion efficiency. It is the role of the Combustion Professional to consider the design aspects of the processes involved in order to achieve an optimum relation between efficiency and emission of pollutants.

Natural gas, once neglected as a practical fuel and burned indiscriminately at oil wells, has observed an usage increase for being, relatively to other fuels, more environmentally friendly. In industrial installations in the United States of America, natural gas combustion is responsible for 45.3% of the energy generated from fuel (Penner and Berlad, 1995), calling upon this topic significant research and practical interest.

Important environmental aspects also appear when disposable material management and associated energy production are considered in connection with incineration applications. The control of hazardous or toxic by-products gains special attention due to human health effects caused by these substances. Since waste material is usually processed in liquid form (Seeker and Koshland, 1990) , combustion of multi-component liquid droplets is of special interest. Further research on the importance of droplet interaction have been indicated as means of increasing the combustion efficiency of incineration devices.

Despite its importance, Combustion emerged as a Science only in the early twentieth century and have observed significant progress with the advent of computer simulations and powerful experimental techniques (Liñán and Williams, 1993). The close relation between the oxidizing reaction, fluid mechanics and transport of mass and energy renders the Combustion Science with increasing complexities as either the basic understanding of the processes evolved or the analysis of practical interest situations are sought. In extending the basis of Combustion Science and reducing the distance between Engineering applications and research topics, Spray Combustion and Vaporization have been indicated as a fundamental research field in an effort to support the development of industrial applications (Penner and Berlad, 1995). Transcritical phenomena, pyrolysis and the behavior of dense or weakly-interacting drops are among the spray combustion topics with further investigation needs.

This research work addresses the effect of droplet and flame interaction on the physical transport characteristics during vaporization and combustion of an infinite stream of droplets. Efficient energy generation and control of pollutants in a wide range of applications, including Diesel and liquid-fueled engines, serve as practical motivations for understanding the basic principles of these phenomena.

In the vast majority of applications, the physical processes of vaporization and combustion are preceded by the breakup of liquid jets in order to increase the condensed phase surface area, and thus enhance mixing with the surrounding gas. The atomization process leads to improved ignition and combustion characteristics. Sprays generated by this process usually involve a large number of droplets and can be classified as dense or dilute based on the dispersed-phase volumetric fraction.

The transport characteristics of dilute sprays are not influenced by the presence of other adjacent droplets and the deviation from the pure isolated behavior, under similar conditions, comes from the interactions with the continuous phase. Droplet interactions in dense sprays, which prevail in practical applications, should be considered in analyzing the system characteristics, since significant changes in momentum, heat and mass transport mechanisms can be expected for both reacting and nonreacting situations.

The droplet interaction phenomena can be understood from the nature of the involved physical process. Energy in the form of heat diffuses and convects from the surrounding ambience or reaction zone to the droplet surface, increasing the liquid droplet temperature and leading to phase-change. Mass diffusion is also present due to species concentration gradients. In a combustion situation, the vaporized liquid is transported to the flame (Stefan Flow) where reaction occurs and heat is released to the ambience and to the condensed phase. Interdroplet effects alter the manner in which an individual droplet receives heat and thus affect its heating and vaporization history. In reacting situations, competition for the ambient oxidant alter the flame position and shape, and variations in ignition delays are influenced by the spray denseness. This physical phenomenon is depicted in Fig.1 for an isolated droplet, as well as for a two-element linear array . For isolated droplets and using simplifying assumptions, an analytical approach can be followed leading to the classical d^2-law

$$-\frac{dR^2}{dt} = constant$$

which has been experimentally validated. Under interactive conditions, analytical treatments are rarely possible due to multidimensionality effects and to the large number of droplets necessary to describe a realistic spray. Experimental works while capable of providing global information on droplet interaction, do not provide detailed characteristics of the physical phenomena. Interaction effects between droplets can be considered in array studies, allowing fundamental information on the process to be obtained from both experimental and numerical approaches.

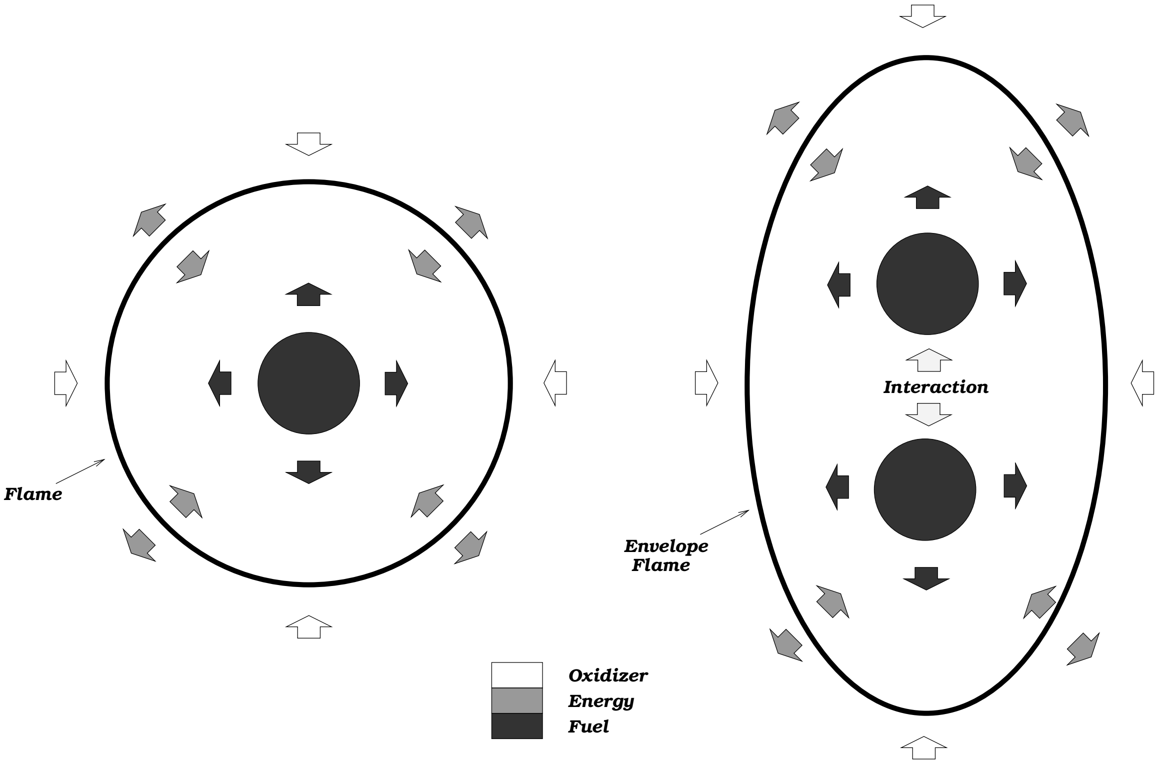

Figure 1: Droplet combustion under isolated and interactive conditions.

2. Droplet Interactive Effects - Subcritical

Efficient energy generation and control of pollutants in a wide range of technological applications are among the important issues motivating the study and understanding of various aspects of liquid spray combustion. In the vast majority of applications, which include Diesel and liquid-fueled engines, the physical process of vaporization and combustion is preceded by the breakup of liquid jets in order to increase the condensed-phase surface area, and thus enhance the transport characteristics with the surrounding continuous phase. This atomization process invariably leads to dense sprays, within which interaction effects and deviations from the isolated droplet behavior (Spalding, 1953, Spalding, 1955) become important, and make pure analytical treatments not applicable.

Reviews of numerical studies of multi-droplet combustion have been presented covering a broad selection of physical situations and stressing the importance of droplet interaction (Sirignano, 1993, Annamalai, 1992).

Theoretical works dealing with burning and vaporization of general arrays in stagnant conditions were performed using the Modified Images Method. The method was initially applied to the vaporization of a nonplanar array of droplets indicating that interaction effects can significantly reduce the vaporization rate and increase the droplet lifetime even in relatively dilute sprays (Labowsky, 1976).

The applied methodology is based on the linearity of the Laplace's Equation, used to model the phenomena, after simplifying assumptions are made, which include the absence of convective and Stefan flows. Initially, the solution is built by the introduction of point sources of the quantities of interest in order to satisfy the boundary condition at the surface of one array droplet while maintaining the other droplet surfaces at the unperturbed infinity value. The procedure is repeated for each element of the array and the general solution is obtained by the superposition of the individual droplet solutions. The difference between the classical and the Modified Images Method resides in the truncation scheme of the obtained series with the intent of reducing computational costs (Labowsky, 1976). Arrays of droplets with different chemical compositions were also studied indicating that positive interaction can arise from the different vapor concentration on the particle surfaces (Labowsky, 1976a). The vaporization rate correction factor was also shown to be linearly dependent on the surface potential of the array elements (Labowsky, 1976a).

An extension of the approach including nonlinear Stefan flow effects was also developed by initially transforming the governing equations into Laplace's form, by the definition of an appropriate potential, and using the Modified Method of Images to solve the resulting equation (Labowsky, 1978). Results are shown for an array of three equidistant droplets. In relation to this work, the droplet surface blowing velocity and heat flux are assumed to be equally affected by the interaction phenomena, thus leaving the droplet surface temperature at the isolated level (Labowsky, 1976b). The interaction phenomenon in arrays of burning droplets was also investigated for different planar symmetrical arrangements and numbers of particles (Labowsky, 1980) . Results show an increase of interaction effects as the number of array droplets increases or the interdroplet distance is reduced and quantify the obtained burning lifetime deviation from the classical d^2-law predictions. Comparison with experimentally obtained results for linear arrays of droplets initially indicate that only qualitative agreement (Labowsky, 1980). Extension of the model in order to better describe the experimental set-up provided a better quantitative agreement with the experimental data (Sangiovanni and Labowsky, 1982) .

Under convective conditions, the presence of neighboring droplets alters the flow field affecting droplet vaporization rate. Results for finite linear arrays of solid burning particles inside tubes indicate an asymptotic behavior of the transfer parameters as the number of droplets in the stream increases (Tsai and Sterling, 1991). The flow field was assumed to be potential and obtained from the superposition of a uniform, coaxial flow with sets of point sources or sinks used to describe the droplets. The source (sink) strengths were obtained from the mass-energy coupling condition at the droplet surfaces and were found interactively with the numerical solution of the energy and species conservation equations. Transformations of the coordinate system were used during grid generation allowing the solution to be sought in a regularly spaced mesh obtained numerically (Knight, 1982). A review of multisphere cylindrical discretizing grids was presented emphasizing that the complexity of the geometry involved imposes difficulties to the numerical treatment of the problem. Linear arrays with spacings between 2 and 8 droplet diameters were studied and results expressed in terms of the droplet surface Nusselt number. Downstream droplets are subjected to more intense interaction effects due to the presence of unburned gases in the convective stream, while the array leading droplets are almost unaffected by the general array characteristics. Results also showed a nonmonotonic behavior of the downstream droplet surface Nusselt number for small spacings. While numerical results available on the literature are discussed, no comparison with experimentally obtained data is included.

Studies on the behavior of finite-linear arrays of droplets and solid spheres in laminar flows were conducted using the finite-element method, covering a wide range of interparticle spacings, fluids and flow conditions. Steady and axisymmetric calculations for three-element arrays indicate that the heat transfer characteristics of the leading sphere, expressed in terms of the local Nusselt number, are similar to the isolated sphere behavior (Ramachandram *et al.*, 1989). Nevertheless, induced recirculation zones may locally enhance leading droplet heat transfer for small spacings. Downstream spheres and liquid droplets are subjected to significant interference effects influenced by the intersphere distances and free stream Reynolds number. Correlations for the interacting sphere Nusselt number are also obtained. In a subsequent work (Ramachandram *et al.*, 1991), fluid dynamics aspects were further analyzed. Results for the separation angle and drag coefficient were presented and compared with isolated particle values. Nonevaporating droplets were used to show the reduction of drag coefficient due to delay on flow separation induced by the liquid-phase circulation.

Surface mass transfer effects were also numerically investigated for arrays of monodispersed droplets (Chiang and Keinstreuer, 1991) and spheres (Keinstreuer and Chiang, 1993). While Hill's spherical vortex was used to describe the liquid-flow motion, droplet surface regression and transient effects were not considered. In general, thermal and hydrodynamic boundary-layers thickening, due to surface blowing, reduces the heat transfer coefficients and the droplet drag, which may ultimately lead to droplet collision. The importance of transient effects and droplet surface regression were also explored for the same geometrical arrangement (Chiang and Keinstreuer, 1992). Liquid- and gas-phase governing equations are solved simultaneously and results indicate that a decrease on interfacial shear leads to internal circulation weakening and increasing importance of conduction within the liquid droplets. Downstream droplet vaporization is impaired by the presence of convected fuel vapor from upstream droplets leading to a significant difference on the droplet radius reduction rate. The methodology discussed above has been extended to more evolved physical problems by including the droplet relative displacement and variable physical properties (Hsucheng and Keinstreuer, 1992, Keinstreuer *et al.*, 1993).

A bi-spherical system of coordinates was used in a purely analytical investigation of interaction effects during the combustion of two fuel droplets (Twardus and Brzustowski, 1977). In this study, Stefan flow convective effects were neglect and a 44% increase on the individual mass vaporization resistance was obtained for the limiting case of touching droplets. The convection effect is estimated to enhance the droplet mass vaporization rate by a factor between 2 and 2.5. Interactive effects on the flame shape are also investigated using the flame-sheet approximation and represent the focus of the presented discussion. Different flame regimes ranging from slightly-distorted individual to fully-merged reaction sheets were observed for interdroplet distances between 10 and 1.5 droplet radii. A flame merging criteria based simply on the reaction stoichiometry was also developed and indicate the existence of a spatial cone which defines the flame regime. Droplets lying within the cone burn enveloped in individual flames while droplets whose surfaces are intersected by the cone present a single reaction sheet.

Analytical and numerical parallel droplet stream studies show a premixed reaction zone acting as ignition source for the stream combustion (Rangel and Sirignano, 1988) and ignition delay and droplet lifetime to decrease proportionally with the lateral stream spacings (Rangel and Sirignano, 1989).

Numerical approaches share the compromise of dealing with the small scale phenomena in the droplet near field and the large scale of the stream, which leads to high computational costs and, thus, limits them to a finite, and usually small, number of droplets.

Droplet-stream combustion has also been the topic of experimental research, and different aspects of interaction effects have been studied. Similarly to the numerical approaches, the small spatial scale of the physical phenomena also introduces complications in experimental works (Faeth, 1983). Droplets in a stream were shown not to follow the classical d^2 vaporization law valid for isolated conditions and buoyancy effects have an important role in the droplet interaction phenomena (Miyasaka and Law, 1981). Combustion experiments conducted under microgravity conditions for pairs of droplets (Mikami *et al.*, 1994) described the history of the different flame regimes and indicated a shorter droplet lifetime when compared to theoretical quasi-steady results, showing the importance of thermal radiation effects. The effect of droplet interaction on the ignition of linear array (Sangiovanni and Kesten, 1976) was studied for a large range of droplet spacings, indicating an increase of up to 4 times in the ignition times for small interdroplet distances. Detailed measurements of the temperature profiles (Zhu *et al.*, 1992, Zhu and Dunn-Rankin, 1992a) for interdroplet distances around 10 droplet diameters show temperature gradients perpendicular to the stream axis in the far field indicating, in this region, a superposition of individual-droplet effects and, therefore a stream-dominated process. This result is explored in the present work when defining the outflow boundary conditions. Results for rectilinear droplet streams under convective conditions showa linear decrease of vaporization rate, obtained from changes in droplet size, for initial droplet spacing between 2 and 10 (Silverman and Dunn-Rankin, 1994). Multi-stream experiments performed for a variety of droplet sizes and spacings show, similarly to the numerical calculations, interacting premixed and diffusion flame fronts and effects of droplet and stream separation (Queiroz, 1990).

3. References

W. Bartok and A.F. Sarofim, *Fossil Fuel Combustion: A Sourcebook*, Chapter 1, John Wiley & Sons, 1991.

N. Chigier, *Energy, Combustion and Environment*, McGraw-Hill, 1981.

S.S. Penner and A.L. Berlad, Fundamental Combustion Research in Support of Industrial Applications, *Energy*, Vol.20, No.4, pp.311-324, 1995.

WM. R. Seeker and C.P. Koshland, Combustion By-product Formation: An Overview, *Combustion Science and Technology*, Vol.74, pp.i-viii, 1990.

A. Liñán and F.A. Williams, *Fundamental Aspects of Combustion*, Oxford Press, New York, 1993.

D.B. Spalding, The Combustion of Liquid Fuels, *Proc. 4th International Symposium of Combustion, Cambridge, MA*, pp. 847–864, Williams and Wilkins, Baltimore, 1953.

D.B. Spalding, *Some Fundamentals of Combustion*, Chapter 4, Butterworths, London, 1955.

W.A. Sirignano, Fluid Dynamics of Sprays, *Journal of Fluids Engineering*, Vol.115, pp.345–378, 1993.

K. Annamalai, Interactive Process in Gasification and Combustion. Part I: Liquid Drop Arrays and Clouds, *Prog. Energy Combust. Sci*, Vol.18, pp.221–295, 1992.

M. Labowsky, The Effects of Nearest Neighbor Interactions on Evaporation Rate of Cloud Particles, *Chemical Engineering Science*, Vol.31, N9, pp. 803–813, 1976.

M. Labowsky, A Method for Determining the Effects of Chemical Composition on the Heat/Mass Transfer Rates of Interacting Spherical Particles, *Proc. 69th Annual Meeting of the AIChE*, Chicago, 1976.

M. Labowsky and D.E. Rosner, Conditions for Group Combustion of Droplets in Fuel Clouds: I. Quasi-Steady Predictions, *Proc. of the Symposium on the Evaporation/Combustion of Fuel Droplets*, American Chemical Society Centennial Meeting, San Francisco, 1976

M. Labowsky, A Formalism Calculating the Evaporation Rates of Rapidly Evaporating Interacting Particles, *Combustion Science and Technology*, Vol. 18, pp. 145–151, 1978.

M. Labowsky, Calculation of Burning Rates of Interacting Fuel Droplets, *Combustion Science and Technology*, Vol.22, pp. 217–226.

J.J. Sangiovanni and M.Labowsky, Burning Times of Linear Fuel Droplet Arrays: A Comparison of Experiment and Theory, *Comb. and Flame*, Vol.47, pp.15-30, 1982.

J.S. Tsai and A.M. Sterling, The Combustion of a Linear Array in a Convective, Coaxial Potential Flow, *Combustion and Flame*, Vol.86, pp.189–202, 1991.

D.D. Knight in *Numerical grid Generation*, Edited by J.F. Thompson, Elsevier, New York, pp. 357–384, 1982.

R.S. Ramachandram, C. Keinstreuer and T.-Y. Wang, Forced Convection Heat Transfer of Interacting Spheres, *Numerical Heat Transfer, Part A*, Vol. 15, pp. 471–487,1989.

R.S. Ramachandram, T.-Y. Wang, C. Keinstreuer and H. Chiang, Laminar Flow Past Three Closely Spaced

Monodisperse Spheres or Nonevaporating Drops, *AIAA Journal*, Vol.29, pp.43–51, 1991.

H. Chiang and C. Keinstreuer, Convection Heat Transfer of Colinear Interacting Droplets with Surface Mass Transfer, *Int. Journal of Heat and Fluid Flow*, Vol.12, No.3, pp.233–239, 1991.

C. Keinstreuer and H. Chiang, Convection Heat Transfer of Closely-Spaced Spheres with Surface Blowing, *Wärme- und Stoffübertragung*, Vol.28, pp.285–293, 1993.

H. Chiang and C. Keinstreuer, Transient Heat and Mass Transfer of Interacting Vaporizing Droplets in a Linear Array, *Int. Journal of Heat and Mass Transfer*, Vol.35, No.10, pp.2675–2682, 1992.

C. Hsucheng and C. Keinstreuer, Computational Analysis of Interacting Vaporizing Fuel Droplets on a One-Dimensional Trajectory, *Combustion Science and Technology*, Vol. 86, pp. 289–309, 1992.

C. Keinstreuer, J.K. Comer and H. Chiang, Fluid Dynamcs and Heat Transfer with Phase-Change of Multiple Spherical Droplets in a Laminar Axisymmetric Gas Stream, *Int. Journal of Heat and Fluid Flow*, Vol.14, No.3, pp.292–300, 1993.

E.M.Twardus and T.A. Brzustowski, The Interaction Between Two Burning Fuel Droplets, *Archiwum Termodynamiki i Spalania*, Vol.8, pp.347-358, Polish Academy of Sciences, 1977.

R.H. Rangel and W.A. Sirignano, Unsteady Flame Propagation in a Spray with Transient Droplet Vaporization, *Proc. 22nd Symposium (International) on Combustion*, pp. 1931–1939, The Combustion Institute, Pittsburgh, 1988.

R.H. Rangel and W.A. Sirignano, Combustion of Parallel Fuel Droplet Streams, *Combustion and Flame*, Vol.75, pp. 241–254, 1989.

G.M. Faeth, Evaporation and Combustion of Sprays, *Prog. Energy Combustion Science*, Vol. 9, pp. 1–76, 1983.

K. Miyasaka and C.K. Law, Combustion of Strongly-interacting linear droplet arrays, *Proc. 18th Symposium (International) on Combustion*, pp. 283–292, The Combustion Institute, Pittsburgh, 1981.

M. Mikami, Kato,H., Sato,J. and Kono,M., Interactive Combustion of Two Droplets in Microgravity, *Proc. 25th Symposium (International) on Combustion*, paper no. 238-117, The Combustion Institute, Pittsburgh, 1994.

J.J. Sangiovanni and A.S. Kesten, Effect of Droplet Interaction on Ignition in Monodispersed Droplet Streams, *Proc. 16th Symposium (International) on Combustion*, pp.577, The Combustion Institute, 1976.

J.Y. Zhu, D. Dunn-Rankin and G.S. Samuelsen, CARS Temperature Measurements in Droplet Stream Flame, *Comb. Sci and Tech.*, Vol.83, pp. 97–114, 1992.

J.Y. Zhu and D. Dunn-Rankin,Temperature Characteristics of Combusting Droplet Stream, *Proc. 24th Symposium (International) on Combustion*, pp. 1473–1481, The Combustion Institute, Pittsburgh, 1992.

M.A. Silverman and D. Dunn-Rankin, Experimental Investigation of a Rectilinear Droplet Stream Flame, *Comb. Sci. and Tech.*, Vol.100, pp.57-73, 1994.

Queiroz, M., The Effect of Lateral Spacing on the Combustion Dynamics and Thermal Structure of an Array of Burning Droplet Streams, *Comb. Sci. and Tech.*, Vol.72, pp. 1–16, 1990.