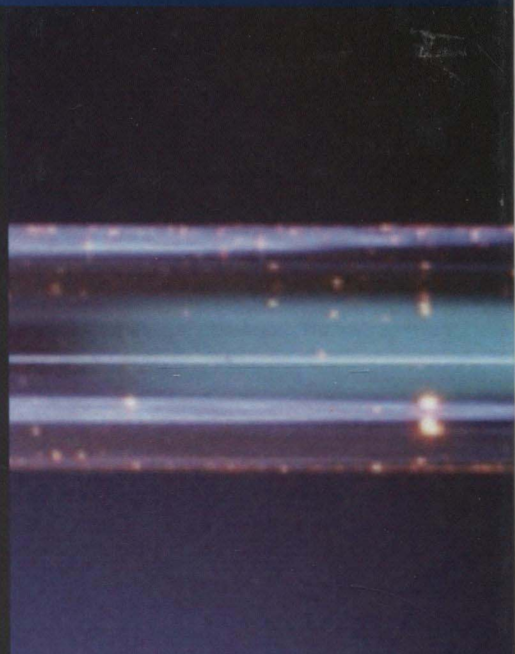
MICROSCALE COMBUSTION AND POWER GENERATION



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Abstract

Recent advances in microfabrication technologies have enabled the development of entirely new classes of small-scale devices with applications in fields ranging from biomedicine (portable defibrillators, drug delivery systems, etc.), to wireless communication and computing (cell phones, laptop computers, etc.), to reconnaissance (unmanned air vehicles, microsatellites etc.), and to augmentation of human function (exoskeletons etc.). In many cases, however, what these devices can actually accomplish is limited by the low energy density of their energy storage and conversion systems.

This breakthrough book brings together in one place the information necessary to develop the high energy density combustion-based power sources that will enable many of these devices to realize their full potentials. Engineers and scientists working in energy-related fields will find here:

- An overview of the fundamental physics and phenomena of microscale combustion;
- Presentations of the latest modeling and simulation techniques for gas-phase and catalytic micro-reactors;
- The latest results from experiments in small-scale liquid film, micro-tube, and porous combustors, micro-thrusters, and micro heat engines;
- An assessment of the additional research necessary to develop compact and high energy density energy conversion systems that are truly practical

KEYWORDS

microscale combustion, flameless combustion, combustion limits, combustion instability, excess enthalpy combustion, small-scale liquid film combustors, micro-tubes and porous combustors, Swiss-roll combustors, catalytic reactors, micro-heat engines, micro-reactors, micro-power generators, micro-thrusters, model aircraft engines, 2-stroke engines, piston engines, heterogeneous combustion, catalytic combustion, conjugate heat transfer, scale-effects on combustion, thermoelectric power generation, micro gas turbine engine, micro-rotary engine, micro-rockets, microfabrication, MEMS

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PREFACE

In 1998, Chang-Lin Tien came to Caltech to give a talk on microscale boiling heat transfer [1]. He had just stepped down after a distinguished term as Chancellor of UC Berkeley and it was clear that he was really looking forward to returning to research. He began by recounting some advice that Llewellen M. K. Boelter, another luminary in heat transfer, had given him many years prior at the beginning his academic career. The gist of Boelter's advice was this: "Go to the extremes. That is where the interesting things will be and don't worry about the applications yet. They will come." Professor Tien went on to explain how his career in high flux heat transfer (which soon became relevant because of the development of nuclear power plants) had begun and that now, for his return to research, he was moving to the other extreme: heat transfer at very small scales. Unknown to everyone in the room then, but true to Boelter's hypothesis, was that rapid advances in microfabrication technology would soon make microscale heat transfer an extremely important topic. Zhigang Suo, a Harvard Professor and a world renowned expert on micromechanics, gave similar advice in 2000: "go microcombustion!"

In some sense then, this book is a result of Boelter's and Zhigang's visionary advice given more than a decade ago. The first two sections focus on what happens to various types of flames when one attempts to stabilize them in small passages. A more careful discussion of "microcombustion" and what "small" means in the context of flames is presented in the introduction. The last section focuses on applications of miniature combustion systems. While there are some applications in chemical processing (in situ generation of hazardous reagents for example), the overwhelming majority is in energy conversion: that is the construction of miniature heat engines and propulsion systems.

That we can think about microcombustion-powered systems at all is due in large part to advances in manufacturing technologies like chemical etching, deep reactive ion etching, chemical vapor deposition, wafer bonding, and so on that allow us to make things with micron-scale dimensions. These manufacturing tools have enabled the miniaturization of all sorts of devices (cameras, telephones, automotive sensors, etc.) and have spawned the general field of "MEMS" which stands for microelectro mechanical systems and "microsystems." Advances in this field enable the functional integration of microelectronic and micromechanical systems on one chip. One successful example is the microchip-based drug delivery system [2]. Advances in integration are also occurring at somewhat larger "mesoscales" with one especially important, power-limited, example being exoskeletons for augmenting human function [3, 4]. Given these successes, it is logical to think about miniaturizing the power/energy source too. But can it be done?

Richard Feynman is often credited for launching the field of MEMS through his now famous talk "There's plenty of room at the bottom." While combustion is mentioned, it is in only one sentence and it is not encouraging: "This rapid heat loss [associated with miniaturization] would prevent the gasoline from exploding, so an internal combustion engine is impossible" [5]. These are concerning words indeed for advocates of microcombustion—especially because they are true! The key question, however, is at what scale they are true since we all know that engines work at the scales of model airplanes and larger. As a result, one important objective of this book is to help developers of combustion-powered microsystems choose sensible sizes for their devices. Another is to determine under what conditions it makes sense to develop completely self-contained combustion-powered devices on a single chip and under what conditions somewhat larger less integrated devices make more sense.

This volume focuses on combustion at small scales—that is in passages with dimensions of a few millimeters or smaller. The main applications are in miniature power sources for devices like those described above. Examples include heat engines [6–9], fuel processors for fuel cells [10–13], and thermoelectric generators [14, 15]. There are also other applications in chemical processing like in situ generation of hazardous reagents [16, 17] but these will not be the focus here.

The distinguishing aspect of this volume compared to others in microsystems [18, 19] is its exclusive focus on fundamentals of microcombustion and thermo-chemical energy conversion. While other books have chapters that address microscale combustion, it is always in the context of much broader applications like power generation or rotating machines and the level of detail is relatively limited. That this book on microcombustion follows those on its broader applications is consistent with how the field developed. The classical concept of the "quenching diameter" as a limiting passage size prevented many combustion researchers from taking the idea of microscale combustion seriously until microfabricators actually built devices at smaller scales and showed that it was in fact possible to sustain reaction. However, because the early efforts were largely fabrication driven, sufficient resources were not available to address the combustion problems (incomplete combustion, flame instability, and excessive heat loss) that were encountered. As a result, another objective of this volume is to give developers of combustion-powered microsystems enough physical insight into the microscale combustion processes to develop suitably efficient and stable microcombustors.

Finally, a volume like this is not produced in a vacuum and there are many people to thank. First and foremost, we would like to thank the authors of each chapter who made time in their busy schedules to assemble their chapters. This is much easier said than done and we truly appreciate their willingness to support this project and the quality of their contributions. Thanks go as well to the many un-named graduate students and research assistants who performed a lot of the foundational work upon which these chapters are based. Second, we would like to thank our external reviewers Drs. Derek Dunn-Rankin and Paul Ronney for making sure that the material measures up technically and for offering their valuable insights. We would also like to thank Dr. Dunn-Rankin and William Sirignano for championing the idea of a book on microcombustion and for making the connection to Momentum Press. Third, we would like to thank Kurt Annen and Aerodyne Research Inc., Josh Collins and Sun Power Inc., Werner Dahm, Alan Epstein, Carlos Fernandez-Pello, Paul Ronney, and Rich Yetter for either supplying or permitting us to use images of their technology in the introduction. Fourth, many thanks go to Exeter team and especially to Joel Stein, Millicent Treloar, Cindy Durand, Destiny Hadley, and the rest of the staff at Momentum Press for their advice, support, and understanding as this project stretched far longer than intended. We truly appreciate your patience and hope that the wait was worth it! Finally, we would like to thank our families and home institutions for their support during this effort. Without you, we would not have been able to complete this project.

Chris Cadou, Yiguang Ju, and Kaoru Maruta Oct. 20, 2013

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INTRODUCTION

MICROSCALE COMBUSTION AND POWER GENERATION

Hardly a year passes without the introduction of another small power-consuming device that has the potential to fundamentally transform people's lives. Examples of the past include mobile computers, telephones, and "smart" phones. That the impact of these devices needs no explaining is perhaps the best testament to their significance. Examples of the present include miniature satellites and unmanned air vehicles (Figure 1) which have moved beyond the military realm to serve as mobile sensor platforms for monitoring everything from traffic flow [1, 2] to agricultural performance [3] to environmental conditions in forests [4, 5]. The data that are collected—but one component of what is sometimes termed "big data"—will help us to understand and improve everything from weather prediction to security [6]. More transformative technologies are on the horizon. For example, in another 10 years it could be common for people to wear electronic devices like Google Glass (Figure 2a) that augment human senses and link them in a more biologically natural way to cyber-data sources. Similarly, people may wear external mechanisms like exoskeletons (Figure 2b) that enhance physical capabilities or permit disabled people to function more normally. In 20 years, large fleets of miniature spacecraft could be launched that increase our reach into the vastness of space in a far more pervasive way than larger manned vehicles ever could. This could increase the probability of success in the somewhat stochastic process of discovering new sources of critical materials—and possibly new habitats.

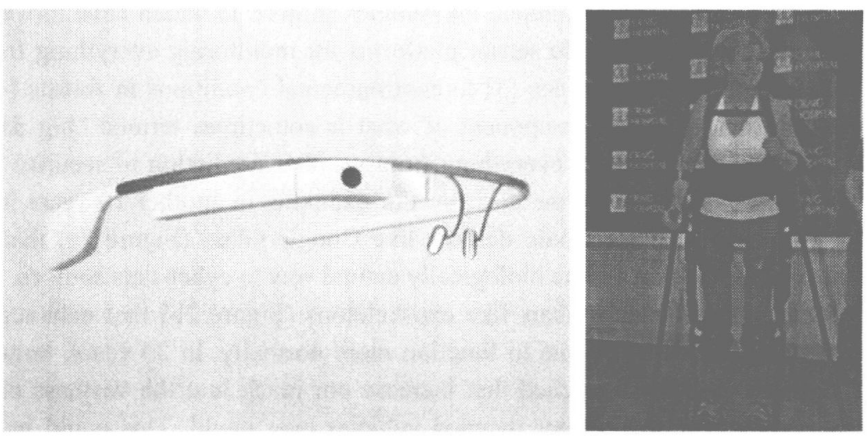
Whether or not these technologies live up to their potential depends to a large degree on the availability of appropriate power/energy sources. They must be compact (i.e., of the scale of the device or smaller) and lightweight enough to be worn or carried, rapidly rechargeable, long-lived, provide power output ranging from several milliwatts to hundreds of watts [7–9] (depending on the application), mass-producible/inexpensive, safe reliable, and power/energy dense. Note that the latter also means thermodynamically efficient.

At present, batteries are the only power sources available at scales suitable for many of these devices. While batteries are efficient (if discharged properly), their relatively low energy densities and long recharge times place significant limits on what the systems they power can ultimately accomplish. For example, the exoskeleton pictured in Figure 2b can operate for only a few hours before needing to recharge. While this is not bad—especially for a person who would otherwise be unable to walk—imagine the difference that being able to walk for a full day as opposed to 2 hours would make to a disabled person.

Interest in miniature combustion-based power systems derives from two factors: the enormous mass-specific energy advantage of liquid hydrocarbon fuels (e.g., gasoline, diesel, and JP-8) over electrochemical materials and advances in MEMS fabrication techniques that are

(a) (b) (c)

Figure 1. Examples of small unmanned air vehicles (UAVs) and satellites. (a) Honeywell T-Hawk UAV intended for battlefield surveillance (from Honeywell Inc. [77]) (b) University of Maryland's powered/controllable Samara intended for surveillance and general environmental monitoring (c) US Air Force XSS-11 microsatellite developed to re-supply and service larger satellites (from Air Force Research Laboratory [78]).



(a) (b)

Figure 2. Examples of wearable devices for enhancing human perception and mobility. (a) Google Glass headset that lets the wearer view various types of information on a miniature display, can take pictures and video from the wearer's perspective, and can connect to the internet. (b) A lower extremity exoskeleton developed by Ekso Bionics to assist people with limited lower body function (from EKSO Bionics [79]).

capable of making "engine-like" components at micron scales.[1] Figure 3 shows that the energy density of a typical liquid hydrocarbon fuel (~44 MJ/kg [10]) is more than 60 times that of the most advanced rechargeable lithium-ion batteries (0.72 MJ/kg [11]). While the very best (and most exotic/expensive) primary batteries can achieve energy densities as high as 1.9 MJ/kg [11], this is still more than a factor of 20 lower than what is offered by a typical liquid hydrocarbon. Therefore, even a relatively low-performing (10 percent efficient) liquid hydrocarbon-based system will outperform the most exotic primary batteries by more than a factor of 2 and

[1]Note that while no group has succeeded in building a working MEMS engine to date, manufacturing processes for building very small machines out of an increasingly wide range of materials are available and continue to evolve.