Thermoacoustics

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Preface

I'm thrilled by the power density and efficiency recently achieved by thermoacoustic engines and refrigerators, and I'm fascinated by some of the latest developments in thermoacoustics: mixture separation via oscillating thermal diffusion (1,2); self-excited oscillating heat pipes ("Akachi" or bubble-driven heat pipes) (3); deliberate superposition of steady flow (4,5). At night I often dream of a future world in which thermoacoustics is widely practiced. One dream had linear-motor-driven thermoacoustic heat pumps atop the hot-water heaters in half the homes in Phoenix, pumping heat from room air into the hot water-the production of a little cooling in the homes was a nice by-product. Another dream featured a small thermoacoustic system next to the liquid-nitrogen and liquid-oxygen dewars in back of our local hospital. This system had a thermoacoustic engine, heated by combustion of natural gas, driving several pulse-tube refrigerators, which provided the cooling necessary to liquefy air, to distill it to produce purified nitrogen and oxygen, and to reliquefy the pure gases for storage in the dewars. A third dream had hundreds of enormous combustion-powered thermoacoustic natural-gas liquefiers arrayed on an offshore platform, using the natural gas (methane) itself as the thermoacoustic working gas and filling a vacuum-insulated supertanker with cryogenic liquified natural gas for transport to distant shores. Yet another dream showed an extensive thermoacoustic apparatus on Mars-a thermoacoustic engine driven by a small nuclear reactor produced 100 kW of acoustic power, which was piped to assorted thermoacoustic mixture separators and refrigerators, splitting atmospheric carbon dioxide and mixed frozen water into pure H_2 and O_2 and liquefying these for use in fuel cells on each of the many robots scooting around building a colony for eventual human habitation.

The dreams are always different, but they have some features in common. First, they all feature low-tech hardware: big pipes welded steel, conventional shell-and-tube heat exchangers, molded plastic, etc. Second, I know that this simplicity is deceptive, because the technical challenge of designing this easy-to-build hardware is extreme. Third, there are no people in these dreams…because I know so few people who are skilled in thermoacoustic engineering today. So, I wake up, afraid that none of this will ever happen, afraid that integrated thermoacoustic process engineering is an opportunity that will never have a chance. So I get up and I write another few paragraphs of this book, hoping to help newcomers learn basic thermoacoustics quickly, so they can go on to design, build, and debug wonderful thermoacoustic systems of all kinds.

This is an introductory book, not a full review of the current status of the field of thermoacoustics. It is evolving from the short course that I gave on this subject t the March 1999 Berlin acoustic meeting. The hardware examples used here to illustrate the elementary principles are thermoacoustics apparatus developed at Los Alamos or with our close collaborators, and the mathematical approach to the gas dynamics and power flows closely follows that pioneered by Nikolaus Rott. (Time pressure induces me to stick with topics most familiar to me! and, indeed, the Los Alamos approach to thermoacoustics has been quite successful.) Many aspects of thermoacoustics will be introduced, in an attempt to help the reader acquire both an intuitive understanding and the ability to design hardware, build it, and diagnose its performance.

At Los Alamos, we have found it most productive to stay focused on experimental and development hardware, while maintaining several abstract points of view including phasor display of acoustic variables, and intuitively appealing picture of gas motion, and an entropy-generation perspective on the second law of thermodynamics. Intuition is important because it helps us humans organize our thoughts. Mathematics is unavoidable, because it is the common language with which scientists and engineers communicate, and it allows us to interpolate and extend our knowledge quantitatively. But experiment is the source of all real truth, so the experiments are our most important and time-consuming activity at Los Alamos. Weaving intuition, mathematics, and experimental results together in this book, I will put strong emphasis on the mathematics, because without this common vocabulary we can get nowhere. Intuition gets second-highest emphasis, as appropriate for an introductory treatment. Experimental results get the least emphasis in this text. But please remember that the mathematical and intuitive discussions presented here are actually distillations of many experiments spanning many decades throughout the world.

Many readers will find that they have only part of the background needed to learn thermoacoustics. Mechanical engineers and chemical engineers may have insufficient acoustics background. They should study an introductory treatment like Chapters 5-10 (and perhaps 14) in *Fundamentals of Acoustics* by Kinsler, Frey, Coppens, and Sanders (6). Acousticians, on the other hand, may need to study something like the first half of *Fundamentals of Classical Thermodynamics* by Van Wylen and Sonntag (7). Someone for whom the expression $i = \sqrt{-1}$ is unfamiliar must begin with a review of complex arithmetic in an engineering mathematics text such as *Advanced Engineering Mathematics* by Kreyszig (8). There is much to learn, so be patient.

We are all deeply indebted to the Office of Basic Energy Sciences in the US Department of Energy for steady, patient, dependable financial support of fundamental thermoacoustics research, dating back 20 years to when the late John Wheatley first led us in this direction. Working with the postdocs and students supported by OBES/DOE to study these oscillating thermodynamic systems at Los Alamos-Vince Kotsubo, John Brisson, Jeff Olson, Mike Hayden, Bob Reid, Phil Spoor. Bob Hiller, Scott Backhaus, Bart Smith and Drew Geller-has taught me most of what I know about thermoacoustics and about how people learn this difficult subject. The engineering and technical skill and creatively of Bill Ward, David Gardner, and Chris Espinoza, and Bill's sophisticated computer skills, have been indispensable, to make rapid progress and to keep our understanding of thermoacoustics realistically grounded in experimental hardware.

Finally, thank you Sharon Dogruel, for brainstorming, steady encouragement, and patience through a year of long days, no whole weekends, and too few holidays I wish I could promise that it won't happen again.

Greg Swift, 1999

Addendum, 2001: Now I must add thanks to the any individuals who have reported typos, math errors, and sources of confusion during the year that “Fourth Draft” has been widely available. My greatest debt by far is due to Robert Keolian and his 2000 thermoacoustics class at Penn State University, who suggested a couple hundred important improvements, including especially a total reorganization and great expansion of what are now the first three chapters.