Pulse Combustion—An Assessment of Opportunities for Increased Efficiency

**D. L. Brenchley
H. J. Bomelburg**

December 1984

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
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226-250	A011
251-275	A012
276-300	A013

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Technologies Division
Office of Energy Systems Research
Conservation and Renewable Energy
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Pacific Northwest Laboratory
Richland, Washington 99352

ACKNOWLEDGMENTS

Mr. Marvin Gunn, DOE/ECUT Program Manager, saw the need for and timeliness of this study and supported it from its initial stages. He was particularly encouraging during the planning of the Pulse Combustion Workshop.

The workshop participants were instrumental in providing information and ideas. In addition to Dr. Herb Bomelburg, one of the authors of this report, the workshop participants included Mr. John Corliss of Battelle-Columbus Laboratories, Dr. Jay Keller of Sandia National Laboratories, Dr. J. A. C. Kentfield of the University of Calgary, Mr. Conrad Yankee of Yankee Engineering, and Dr. Ben Zinn of Georgia Institute of Technology. At the workshop, these participants reviewed this report when it was a working paper and provided essential technical ideas and advice on pulse combustion.

Dr. Herb Bomelburg is to be commended for his keen interest and enduring effort throughout the study.

Vicki Lee edited the report, and in doing so provided many contributions that aid its accuracy and make it easier to read.

D. L. Brenchley
Project Manager

PREFACE

This study is being completed for the Division of Energy Conversion and Utilization Technologies (ECUT) within the Department of Energy (DOE). The division's mission is to identify and research long-range technology concepts that are attractive for more efficient energy use. To meet its goals, the ECUT staff established a planning and systems analysis project that was responsible for conducting this study.

This report will become one of a series of studies in support of the ECUT research planning effort. Other documents in the series contain assessments of energy conservation technology areas, methods to appraise research projects for support, and data reference sources. Publications from this project include the following:

- Abarcar, R. B., G. J. Hane and D. R. Johnson. 1984. ECUT Energy Data Reference Series: High-Temperature Materials for Advanced Heat Engines. PNL-5193, Pacific Northwest Laboratory, Richland, Washington.
- Abarcar, R. B., G. J. Hane and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Lightweight Materials for Ground Transportation. PNL-5192, Pacific Northwest Laboratory, Richland, Washington.
- Bomelburg, H. J. 1983. Efficiency Evaluation of Oxygen Enrichment in Energy Conversion Processes. PNL-4917, Pacific Northwest Laboratory, Richland, Washington.
- Chockie, A. D., et al. 1983. "An Overview of Research Requirements for Stationary Combustion Systems." In Proceedings of the 18th Intersociety Energy Conversion Engineering Conference, pp. 2092-2098. American Institute of Chemical Engineers, New York, New York.
- Chockie, A. D., and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Boilers. PNL-5195, Pacific Northwest Laboratory, Richland, Washington.
- Hane, G. J. 1983. Efficiency Evaluation of the Direct Injection Stratified Charge (DISC), Dilute Homogeneous Charge (DHC), and Direct Injection Diesel (DI Diesel) Engines. PNL-4568, Pacific Northwest Laboratory, Richland, Washington.
- Hane, G. J., et al. 1983. A Preliminary Overview of Innovative Industrial Materials Processes. PNL-4505, Pacific Northwest Laboratory, Richland, Washington.

- Hane, G. J., et al. 1984. A Review of Studies of Research Opportunities in Energy Conservation. PNL-4571, Pacific Northwest Laboratory, Richland, Washington.
- Hane, G. J., and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Otto Cycle Engines in Transportation. PNL-5191, Pacific Northwest Laboratory, Richland, Washington.
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- Vitullo, M., C. Winter and D. R. Johnson. 1984. Executive Information System. PNL-5190, Pacific Northwest Laboratory, Richland, Washington.
- Young, J. K., E. A. Griffin and J. A. Russell. 1984. Opportunities for Energy Conservation Through Biotechnology. PNL-5295, Pacific Northwest Laboratory, Richland, Washington.
- Young, J. K., and D. R. Johnson. 1984. ECUT Data Reference Series: Ammonia Synthesis, Energy Use and Capital Stock Information. PNL-5194, Pacific Northwest Laboratory, Richland, Washington.

D. L. Brenchley
Project Manager

SUMMARY AND CONCLUSIONS

Pacific Northwest Laboratory (PNL) conducted this study for the Energy Conversion and Utilization Technologies (ECUT) Division of the Department of Energy (DOE). The purpose of the study was to assess pulse combustion technology and its potential usefulness for improving energy efficiency and alternative fuel use.

In pulse combustion, burning occurs in a tube (combustor) in an oscillatory manner. In a typical practical application, a gas-air mixture is ignited within a combustion chamber at one end of the tube, creating a pressure pulse that closes the air and gas inlet valves and ejects combustion products at the rear end of the tube. The subsequent pressure drop within the combustion chamber reopens the valves and draws in more air and gas, which is ignited by residual hot gas left by the previous ignition. This cycle then repeats itself indefinitely at a frequency typically around 50 Hz. There are many variations to this process, depending on the type of fuel and application.

Although pulse combustion is not a new concept, its inherent advantages, which are high combustion and thermal efficiency, high combustion intensity, and high convective heat transfer rates, have not been widely used in applications. In this study, PNL identified the barriers to developing and using pulse combustion and then recommended the R&D activities needed to begin removing these barriers. New and/or particularly promising applications of this technology were also identified and described.

Several barriers hinder the development and use of pulse combustion technology: its noise, a lack of awareness of the technology, lack of design and evaluation procedures, lack of credibility, the higher cost of pulse combustion equipment in comparison to conventional combustors, and the lack of an infrastructure to move the technology into the market place. For some of these barriers, one or more specific R&D recommendations that are consistent with ECUT goals were identified:

- Noise Abatement - One of the most negative attributes of pulse combustion is its intense noise (up to 140 decibels). Noise levels must be reduced below 55 to 60 decibels before pulse combustion can become

more widely acceptable. To reduce noise levels as far as possible, it is therefore recommended that systematic research be conducted to investigate, e.g., phase-synchronized pulse combustion in parallel and other promising approaches to noise abatement.

- Design and Evaluation Procedures - Mathematical models for design and scale-up do not exist. Therefore, a primary R&D goal should be to develop analytical models from basic principles in fluids and combustion chemistry to eliminate extensive trial-and-error development. Methods for scaling combustors also need to be developed. With such methods, reliable conclusions could be drawn from model testing at reduced scale. Because drying is an excellent application for pulse combustion, prototype analytical models should be developed to describe the drying process. This would aid in designing units for drying a wide range of materials.
- Credibility - To date, pulse combustion using natural gas has established some credibility, but experience with liquid and solid fuels is limited. Additional R&D should be conducted using a wide range of alternative fuels, including coal, lignite, peat, wood, and liquid fuels. Subsequently, multiple fuel combustion should also be investigated.
- Awareness and Constituency - Except for a few engineers who have a special interest in pulse combustion, the technology is still largely unknown to industry and potential users. As a result, a sufficient constituency in engineering, manufacturing and marketing areas does not exist to advocate the technology, even though it offers marked energy savings. As an initial step, a systems analysis study of critical industrial applications should be conducted. Such a study would identify and describe critical industrial applications that would be innovative, energy-efficient and cost-effective. Taking this step would increase awareness and would begin to develop a large constituency.

Several U.S. commercial applications of pulse combustion do exist. For example, Lennox Industries, Inc., and Hydrotherm, Inc., are presently marketing

gas-fired space and water heaters, respectively. Also, at least two companies (Sonodyne and Sonic Corporation) market units for drying yeast. Several other new commercial units are under development, such as residential space heaters, deep-fat fryers, griddles, and water heaters.

Several key opportunities that are not currently being actively pursued also were identified in this study:

- Alternative fuels such as pulverized coal, lignite, wood chips, and other low-grade fuels may be more effectively used in pulse combustion systems than in conventional systems.
- Pulse combustion units could be applied for steam raising and power generation applications; the number of operating combustors would be changed according to the load.
- Because of the increased turbulent heat and mass transfer in pulsating environments, pulse chemical reactors could become important applications for such areas as calcination, catalytic processes and coal gasification.
- Pulse combustion in fluidized beds is another potential area of application. The pulsations would increase mixing and thereby improve heat and mass transfer in the bed.

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1.0 INTRODUCTION

It has been known for a long time that combustion processes do not always proceed under steady-state conditions but oscillate more or less violently. Usually such combustion instabilities are highly undesirable because they normally generate strong noise and vibrations, and special measures have to be taken to avoid damage to the combustion equipment. Such undesired combustion-driven oscillations have been widely reported because they occur in gas turbines, rocket engines, flares in refineries, blast furnaces, etc. However, more than half a century ago these pulsating combustion phenomena were found to have some advantages under certain conditions and for special applications. The main advantage that has been demonstrated is improved combustion efficiency and the resulting fuel savings. Therefore, under controlled conditions, pulse combustion is desirable from an energy conversion perspective.

In pulse combustion, burning occurs in a tube in an oscillatory manner,^(a) in contrast to the steady-state combustion used in most boilers and furnaces. In most pulse combustors the combustion occurs near the closed end of a tube where valves operate in phase with the pressure amplitude. Within the combustion zone, both the temperature and the pressure oscillate around a mean value.

The development of practical applications of pulse combustion has been hampered because effective design requires a particular combination of the combustor's dimensions, valve characteristics, fuel/oxidizer combination, and flow pattern. Pulse combustion does have some inherent advantages for energy conversion efficiency, such as high combustion and thermal efficiency, high combustion intensity, and high convective heat transfer rates. Also, with pulse combustion, a pressure boost can occur without using a blower. This allows the use of a compact heat exchanger that includes a condensing section without using a chimney. In the last decade, these features have revived interest in

(a) Occasionally pulsations are generated by external means in contrast to self-excited oscillation. In such cases, expressions such as "pulsed" combustion may be used. However, a clear distinction between the "pulse" and "pulsed" combustion is not always made because the basic physical phenomena are quite similar.

research and development (R&D). For example, this R&D has resulted in a pulse combustion air heater introduced commercially for domestic use by Lennox in 1981 (Adams 1982), and a pulse combustion hydronic unit developed by Hydrotherm, Inc. Such devices can operate at 92% to 96% efficiency, whereas most other currently manufactured gas hot water heaters usually operate from 55% to 78%. Such applications demonstrate the magnitude of the potential for energy savings with pulse combustion. Additional details on recent and current activities are presented in Sections 3.1 and 3.2.

This work is part of the Systems Analysis Project at Pacific Northwest Laboratory (PNL). This effort was conducted for the Energy Conversion and Utilization Technologies (ECUT) Division of the Office of Energy Systems Research, U.S. Department of Energy (DOE). One of the purposes of the project is to assess advanced technologies that support the goals of improved energy efficiency and alternative fuel use.

The report is comprised of four chapters and an appendix. In Chapter 2.0, the results of the literature review on pulse combustion are discussed. Chapter 3.0 summarizes current, near-future, and potential key opportunities for pulse combustion applications. The barriers to developing and using pulse combustion technology are discussed in Chapter 4.0, along with R&D needs. The appendix contains the proceedings of a pulse combustion workshop held in May 1984 in Seattle, Washington. At that workshop seven key professionals in the pulse combustion field discussed pulse combustion applications that support ECUT goals, the main technical problems that need to be resolved to meet ECUT goals, and new project ideas that would be consistent with those goals.

2.0 REVIEW OF THE LITERATURE ON PULSE COMBUSTION

To obtain an overview of the present status of pulse combustion research and technology, PNL conducted a systematic search for pertinent literature published since 1972. That search involved the following data banks: DOE, National Technical Information Service (NTIS), Engineering Information Inc., chemical abstracts, and patent abstracts. Of the resulting 400 abstracts, 20% to 30% were examined further. The remaining abstracts were mainly either foreign language publications or duplicate listings. Many of the relevant papers or reports revealed in the search are listed in the reference and bibliography section of this report. This chapter contains brief historical and technical overviews of pulse combustion as viewed from the literature. Following the overviews, several pulse combustion configurations are discussed and shown.

2.1 HISTORICAL OVERVIEW

The first European papers on pulsating combustion were published nearly a century ago. Work was rather sporadic until the 1930s, when P. Schmidt in Germany started experimenting with oscillating combustion in simple straight tubes. This work eventually led to what is probably the most famous pulse combustion system, the V-1 buzz bomb of WWII. At that time, F. H. Reynst also started publishing a series of papers describing various schemes of pulse combustion for a wide variety of engineering applications. Although most of his ideas were not backed up with thorough analytical or experimental work, many eventually were proven to be well-founded.

The initial work in the post-WWII development was directed toward thrust generation (pulse jets) for aircraft or missile propulsion. Societe Nationale d'Etudes et de Construction de Moteurs d'Aviation (SNECMA) in France was particularly active in this field, and in the U.S. the Defense Department (U.S. Navy) and the National Advisory Committee on Aeronautics (NACA) also developed some interest. However, because the newly developed gas turbines with steady combustion proved to be highly successful, the interest in pulse combustion decreased considerably worldwide in the late 1950s. Only a few laboratories and individuals maintained pulse combustion work, but not for thrust

generation. That goal was to use it for general improvement of combustion efficiency and for purposes such as those proposed by Reynst (1961).

Most prominent among the institutions for maintaining interest during the 1960s were the University of Sheffield (England), a few Soviet institutes, Rhurgas in Germany, and the American Gas Association Laboratory in the U.S. In 1971 when the first International Symposium of Pulse Combustion was held in Sheffield, only about 40 participants attended. Since then, the general interest in pulse combustion has again increased considerably, presumably because of the sharply rising oil prices since 1973.

During the 1970s, the emphasis on energy conservation expanded pulse combustion work considerably in the U.S. Many organizations (particularly DOE and the Gas Research Institute) funded R&D work at installations throughout the U.S., and private industry also became involved. During this period, the U.S. became the leader in the field, as demonstrated by the second and third symposia on pulse combustion. The U.S. had many participants at those symposia, and many of the papers presented were from U.S. contributors. The second symposium on pulse combustion was held in 1979 at Argonne National Laboratory (ANL) with an attendance of about 100, and about 300 attended the third symposium in 1982 in Atlanta (organized by Battelle-Columbus Laboratories). The increasing number of symposium participants indicates an increased general interest in the field.

Table 2.1 lists the various centers that have been or still are contributing to pulse combustion development. Although the table is not complete, the more prominent organizations probably have been listed. The table is divided into three main categories: 1) university-type institutions doing mostly theoretical and experimental research; 2) various government-owned or government-sponsored (non-university type) organizations that are responsible for mostly development-type testing; and 3) industrial companies that are in the business of developing, building and selling pulse combustion equipment for practical use. Organizations that are active at present are identified by * in this list.

TABLE 2.1. A Partial Listing of International Centers for Pulse Combustion R&D

Universities (applied and theoretical research)	Government Agencies or Laboratories (sponsoring or performing major R&D projects)	Industrial Institutions (mainly hardware development)
Sheffield, England ^(a)	SNECMA (France)	Shell Lab (UK)
Bradford, England	DOE (ANL, BNL, ORNL, PNL) USA	BP (UK)
Bath, England	AGA* (USA)	Jetsonics, CA
Calgary, Canada*	GRI* (USA)	Sci. Appli., CA
Brest, USSR*	BoM (USA)	Lennox*, TX
Many other USSR	Various power	Aer. Air Filter
Institutes*	companies, USA	Hydrotherm, NJ*
Weimar, DDR*	Various power	Bendix, NY
Gdansk, Poland	companies, Germany	Martin Industries, AL*
Peking, China	Various power	Whittaker, CA
Georgia Tech* (USA)	companies, USSR	Lucas-Rotax Ltd., Canada
Purdue (USA)	Battelle-Columbus,* (Frankfurt, Geneva and Northwest)	Kitchen (private), Canada
Cleveland State (USA)	A. D. Little	Yankee, CT*
Oregon State (USA)	U.S. Navy	MAN (Germany)
Syracuse (USA)	Department of Mines (Canada)	Argus (Germany)
Durham, UK	Cornell Aero Laboratory (U.S.)	Eberspachter (Germany)*
Naval Eng. College, UK	<u>Sandia*</u>	Motan GMBH (Germany)*
Berlin, W. Germany		Turbopuls (Switzerland)
Technion, Israel		Vulcan-Hart, KY*
India (various)		State Industries, TN*
Japan (various)		Weil-McLain, IN*
Pretoria (S. Africa)		Sonodyne, OR*
CSSR		Sonic Corporation, ID*
		Soundrive Empire Company, CA
		Hiller Aircraft Company

(a) Many centers are no longer active. The most active contributors are underlined. Those still active are identified by *, although for some places, current involvement (if any) is unknown. The sequence of the listings is random.

Tables 2.2 and 2.3 list the types of R&D and applications for pulse combustion. Table 2.2 lists the disciplines and categories that are involved in a comprehensive study of pulse combustion. Sample references are provided for each category. As the table indicates, some categories that are generally concerned with the more basic aspects of pulse combustion have been studied more extensively than others. Some of the categories that have received little attention will probably gain importance as the technology moves from the laboratory to the commercial sector. Because potential applications of pulse

TABLE 2.2. General R&D Categories for Pulse Combustion

Category	Comments	Sample References
1. General reviews	Presented from various viewpoints.	Goldman and Timmat 1981; Keller 1954; Lembcke 1953; Marzouk and Kentfield 1974; Putnam 1971; Putnam 1979; Reader 1978; Zinn 1984
2. Theoretical treatments including computer models	Treatment has generally become more sophisticated recently.	Carrier 1955; Dhar et al. 1982; Edelman et al. 1979; Gill and Bhaduri 1978; Hadvig 1971; Hessel et al. 1983; Roginsky 1971; Schulz-Grunow 1947; Winiarski 1971
3. Experimental and test work on burners	Most work on pulse combustion falls into this category.	Alhaddad and Coulman 1982; Clinch and Egbert 1979; Coulman et al. 1982; Kentfield 1982; Porter 1967; Sommers 1958; Walseley and Porter 1967; Zinn 1984
4. Heat transfer enhancement	Results are controversial; effects may have been exaggerated.	Ahrens 1979; Alhaddad and Coulman 1982; Bloomquist 1982; Clarke, Beale and Everson 1971; Hanby 1969; Lalwani et al. 1979; Leistner et al. 1969
5. Inlet valves	Mostly mechanical flapper valves (check valves).	Briffa and Staddon 1982
6. Valveless combustors	Devices known as aerodynamic valves. A relatively large amount of experimentation has been done here, not always with success. Vortex valves may be promising.	Kentfield 1982; Kentfield et al. 1979; Kentfield and Read 1979; Lockwood 1982; Syred and Tippetts 1973
7. Noise emission and other environmental aspects	Have been given rather extensive attention lately. In many combustors, pulsations are not tolerable.	Belles et al. 1982; Chui and Croke 1979; Dhar et al. 1979; Seebold 1975

TABLE 2.2. (contd)

Category	Comments	Sample References
8. Practical applications	Covers a wide area; therefore, see separate listing. Some applications have never been fully investigated or tried out at full scale. See also Putnam's list (Putnam and Locklin 1981) and Table 2.3.	Francis et al. 1963; Podymov et al. 1978; Putnam and Locklin 1981; Severyanin 1982
9. Combustion efficiencies and energy conservation	Such work would show the potential benefits of pulse combustion and justify further development efforts in this field.	Bonne and Patani 1979
10. R&D needs	Specifically points out areas not yet fully understood and the consequences thereof.	Belles 1979; Kentfield 1979; Woodworth 1979
11. Obstacles against widespread use	Not yet systematically investigated. Would show why pulse combustion has not found wide acceptance.	--
12. Operation and safety controls	Mainly covered by patents.	--
13. Problems of scale-up	Little known about this. Further R&D needed.	--
14. Long-term reliability	Little known about this. Further R&D needed.	--
15. Novel and/or untried ideas	Some ideas appear to be very promising.	(see listing in App. A)
16. Undesired pulsation	Occurs occasionally in combustion processes but must be avoided for various reasons.	Dixon et al. 1970; Hessel et al. 1983; Kazantsev and Yakovenko 1976; Pariel et al. 1970; Putnam 1971; Seebold 1975; Tarakanovskii and Krugov 1975
17. Pollution control	Reduction of NO_x and SO_x .	Faesser and Rudnicki 1983; Schachenmeyer and Starke 1965; Belles 1979

combustion cover a wide area and involve many types of design configurations, Table 2.3 lists in greater detail applications that have been mentioned or described in the literature. Again, the number of pertinent references listed in each category indicates areas that have received the most attention to date.

Besides the U.S.'s participation and contributions at the second and third symposia on pulse combustion, the extent of the U.S.'s activity in pulse combustion can be demonstrated in its patent activity. For example, various patents recently have been assigned to GRI, Lennox, Bosch, B&W, Shell Oil, Robert Shaw Controls, and Jetsonic. Other patents have been assigned to various individual inventors, and more patents are pending. These patents generally concern design details pertaining to boilers, dryers, control systems, air furnaces, mist generators, pulse combustion afterburners, resonant exhaust systems, pulse combustion with condensing heat exchangers, pulse combustion monitoring systems, specific geometrical configurations, etc. Because pulse combustion has aroused worldwide interest, many foreign patents also exist. Most of the original patents have already expired. (The original patent on pulsed combustion was obtained by Reynst in 1937 in Germany).

2.2 TECHNICAL OVERVIEW

A complete understanding of pulse combustion is difficult to achieve because it simultaneously involves several disciplines, and few scientists and engineers, if any, are true experts in all these fields simultaneously. The disciplines involved in pulse combustion include thermodynamics, fluid mechanics, combustion chemistry, acoustics, mechanical engineering, and possibly a few others such as environmental safety.

Most of the published basic papers on the pulse combustion deal with only certain aspects authoritatively, while making more or less subjective assumptions on others. The bulk of the literature describes test results with only tentative or incomplete explanations on a fundamental basis. Therefore, currently there is a great deal of empirically obtained data, but it applies only to a very limited range of configurations.

TABLE 2.3. Pulse Combustion Applications (some may overlap)

Category	Comments	Sample References
1. Space/water heating for domestic and commercial application	Mainly gas fired	Adams 1982; Bloomquist 1982; Johnson et al. 1984; Kitchen 1979; Kitchen 1982; Lawton et al. 1982; Locklin and Hazard 1980; Stephens 1983; Thrasher 1983; Vogt et al. 1978, 1980; Reay 1969; Whitlock et al. 1982
2. Coal burning and lignite-burning furnaces	Burned as coal dust or in larger particles	Belter et al. 1969; Hanby and Brown 1968; Zinn et al. 1979; Zinn et al. 1982a, 1982b
3. Wood-burning combustion	Also for refuse burning	Zinn et al. 1982
4. Heat exchangers	Including heat pumps	Lockwood 1982
5. Dehydration and drying	e.g., fruits, vegetables, grain, sand/bricks, lignite, wood	Belter 1971; Lockwood 1979; Muller 1967; Tamburello et al. 1982
6. Fog (mist) generation Smoke generation	e.g., for spraying crops for military operations	Mutchler 1982, Persechino 1959
7. Chemical reactors	not yet used on a large scale	Mueller and Stark 1977; Rudolph et al. 1978a, 1978b
8. Coal gasification	not progressed beyond R&D stage	Traenker 1953
9. Steam raising	not progressed beyond R&D stage	Babkin 1965; Corliss et al. 1982; Putnam and Locklin 1981
10. Gas turbines	not progressed beyond R&D stage	Kentfield 1971; Kentfield et al. 1976; Porter 1958; Swithenbank, Brown and Saunders 1971; Marchal 1968
11. Power generation	not progressed beyond R&D stage	Reynst 1954; Swithenbank, Brown and Saunders 1971; Swithenbank et al. 1975
12. Thrust generation and conversion to mechanical energy	e.g., for jet propulsion	Aldag 1965; Belter et al. 1969; Bertin 1953; Marchal 1966, 1968
13. Miscellaneous other applications	e.g., portable heaters, heat exchanger cleaning, vehicular heating, deep fat fryer, griddles	Desty and Boden 1971; Huber 1964; Johnson et al. 1984; Kentfield 1977; Ringer, Lane and Slawinski 1971

2.3 CONFIGURATIONS FOR PULSE COMBUSTION

In all pulse combustion applications, the basic principle is essentially the same^(a) (Figure 2.1). Fuel and air are admitted to a combustion chamber through more or less effective one-way valves. A pressure wave, generated by the initial ignition, travels down the exhaust tube. A partial vacuum is caused in the combustion chamber, which then draws in additional fuel and air. At the end of the exhaust tube, the pressure wave is partly reflected, resulting in some compression of the gas in the combustion chamber where the newly admitted fuel/air mixture is ignited, presumably by mixing with the hot gases of the preceding cycle. The cycle then repeats itself indefinitely. The cycle phase is timed such that the geometrical combustion chamber/exhaust tube configuration is acoustically at resonance.

Many configurations have been proposed and tested over the years. In particular, the "aerodynamic valves," which generate higher flow resistance for the backflow than for the ingoing flow, often have been tried as a substitute for the mechanical check valves. They are most useful primarily in propulsion devices, such as the "pulse-jets." Figure 2.2 shows the phases of a pulse combustion cycle that uses such aerodynamic valves (Corliss et al. 1982). Figure 2.3 shows four basic combustor configurations that have commonly been used in practical applications (Briffa and Staddon 1982).

The most frequently used combustor applications are the various types of air and water heaters. Figure 2.4 shows, for example, a pulse combustion water heater developed at Purdue University (Dhar et al. 1982; Vogt et al. 1978). The upstream and downstream decoupling chambers help to reduce the noise that is normally emitted with oscillating combustion processes. The solid rods, "corebusters," inserted into the exhaust pipes have the effect of increasing the flow velocity and thereby the heat transfer to the walls of the water jacket. Figures 2.5 and 2.6 show the schematic and the actual configurations of a gas-fired boiler developed by industry (Whitlock et al. 1982). A hot-air furnace (also gas-fired) that is commercially available is shown in Figure 2.7 (Adams 1982).

(a) The Rijke tube (Figure 2.3d) is based on a slightly different principle as thermoacoustical oscillations are generated by a heated wire screen, placed in the lower half of an open-ended vertical pipe.

Block Diagram Model

FIGURE 2.1. Basic Principle of Pulse Combustion (Coulman et al. 1982)

FIGURE 2.2. Operating Phases of an Idealized Pulse Combustor
-- Aerovalved Type (Corliss et al. 1983)

FIGURE 2.3. Four Different Types of Pulse Combustor Geometries
(Briffa and Staddon 1982; Feldmann 1968)

FIGURE 2.4 Top View of Purdue Pulse Combustion Water Heater (Dhar et al. 1979)

FIGURE 2.5. Operation of Hydro-Pulse Boiler (Artist's sketch)
(Whitlock et al. 1982)

FIGURE 2.6. Hydro-Pulse Boiler Cutaway
(Whitlock et al. 1982)

① AIR INTAKE	⑦ EXHAUST PIPE
② COMBUSTION CHAMBER	⑧ GAS VALVE
③ AIR DECOUPLER	⑨ GAS DECOUPLER
④ VENT PIPE	⑩ CONDENSING HEAT EXCHANGER
⑤ BLOWER	⑪ CONTROL BOX
⑥ EXHAUST DECOUPLER	⑫ FILTER

FIGURE 2.7. Schematic of Lennox Pulse Combustion Furnace (Adams 1982)

3.0 OPPORTUNITIES FOR PULSE COMBUSTION TECHNOLOGY

This chapter summarizes current, near-future, and potential opportunities for pulse combustion applications. In Sections 3.1 and 3.2, existing and near-commercial pulse combustion systems are described. The major companies marketing this equipment include Hydrotherm and Lennox, Inc. The information presented in those sections was primarily obtained through telephone conversations with company representatives, review of company literature, and discussions in the Pulse Combustion Workshop (see Appendix A). In Section 3.3 several key opportunities for pulse combustion applications, as reflected by current developmental activities, are described.

3.1 EXISTING COMMERCIAL PULSE COMBUSTION SYSTEMS

Over the years, many industrial companies have made attempts to develop and manufacture pulse furnaces and hot water heaters. The initial emphasis has been on home heating units. Pulse combustion has also been applied to drying processes.

Some of the attempts to apply pulse combustion to home heating units were supported by organizations such as the American Gas Association (AGA) and the Gas Research Institute (GRI). For a short period in the late 1970s, DOE also sponsored R&D work to promote the development of a pulse furnace. This work was administered through three national laboratories: Argonne National Laboratory (ANL), which conducted some in-house research, Brookhaven National Laboratory (BNL), and Oak Ridge National Laboratory (ORNL). The only two companies presently marketing pulse combustion heaters in the U.S. are Hydrotherm, Inc., in New Jersey and Lennox Industries, Inc., in Texas.

Hydrotherm, Inc., offers gas-fired heating systems ranging from 50,000 to 150,000 Btu/hr under the trade name Hydropulse^(a). These units have been commercially available since about 1980, after two gas companies tested them in private homes in New York and Minnesota. The design apparently is a follow-on to a Canadian model that was offered under the name "Pulsamatic" from about

(a) Trademark of Hydrotherm, Inc. of New Jersey.

1960 to 1966 by Greensteel Ltd. of Winnipeg. That model had been developed by Lucas Rotax, Ltd. (Toronto) and, in turn, was an out-growth of one called "Swingfire," developed during the early 1950s in Germany and based on the V-1 buzz bomb of World War II. From the early 1950s to the present, this particular development was encouraged by J. A. Kitchen of Canada and was largely financed by private industry.

A pulse combustion furnace that is now offered by Lennox, Inc., was originally developed under the sponsorship of the AGA, starting in 1978. Later, GRI furthered the development. Extensive field tests were conducted on the resulting system, and commercial production, licensed to Lennox, began in 1982. Input capacities range from 40,000 to 130,000 Btu/hr, and purchase costs roughly range from \$2000 to \$3000. Lennox is currently conducting an active advertising campaign for this furnace.

In Germany, several versions of the already-mentioned "Swingfire" device have been available since about 1950 (Huber 1951). Currently, they are marketed by the Eberspächer company in Esslingen, Germany. These portable devices can be adapted to many end uses. In particular, they have been used for rapid heating of commercial vehicles (e.g., fire trucks), small buildings and tents. Other applications include de-icing and rapid water heating. Power levels are typically about 600,000 Btu/hr (175 kW). Some Swingfires operate at 90 Hz and may be heavily loaded. In their combustion chambers, pressures can oscillate between 0.75 and 1.4 atm absolute (10.5 and 20 psia). Consequently, the peak exit velocities of the combustion gases can reach 150 m/sec. The exhaust gases are therefore able to drive small turbines, which in turn drive fans to circulate the air through heat exchangers when a unit is used for air heating (Huber 1964). Similar devices are marketed by Motan GMBH in Germany.

In the USSR many pulse combustor applications have been reported (Severyanin 1971, 1982). These applications include soot cleaning, fume suppression, burning rate enhancement of various particulate fuels, particle coagulation, fluidized bed combustion, etc. Detailed descriptions of the various devices are difficult to obtain because most of the pertinent publications

are in Russian. However, most of the devices apparently were built for special industrial applications (possibly one of a kind) and have not been manufactured for sale on the open market.

Among the other U.S. companies that also pursued development of pulse combustion heaters has been the Whittaker Corporation with its now defunct Shock Hydrodynamics Division near Los Angeles. Their original goal was a commercial pulse combustion furnace with a power level of about 400,000 Btu/hr. Development was started in 1980 and was partly sponsored through DOE^(a) funds (via BNL and ORNL) and also by American Appliance Manufacturing Corporation. A functioning prototype of 200,000 Btu/hr was built, but by early 1983 American Appliance, which intended to market the product, decided otherwise for business and financial reasons. According to Whittaker management, no technical problems were involved. Shock Hydrodynamics was shut down, and the prototype furnace was shipped to A. O. Smith of Milwaukee on advice from ORNL.

A. O. Smith had shown some interest in pulse combustion development and independently verified the performance of the pulse combustion heater built by Shock Hydrodynamics and turned over to them. Presently, they are conducting a cost analysis on several new furnaces (both conventional and pulse) to determine which one they should market. Results of this study are expected by the end of 1984. If they are favorable, A. O. Smith would build a scaled-up (400,000 to 500,000 Btu/hr range) prototype, which they would expect to test in 1985. A. O. Smith is using its own funds to conduct this work.

Yankee Engineering Company has been active in developing pulse burners since 1976. A small (30,000 Btu/hr) propane-fired prototype was lab-tested in 1978, and a larger gas-fired burner for heating and providing domestic hot water was built. For about 2 years partial support was provided by DOE^(a) through BNL and by industrial companies. Yankee is presently active in developing an "integrated" system for solar and pulse combustion hot water and space heating, particularly for homes in the Northeast. The sponsor of the current activity is an unnamed furnace manufacturer.

(a) Specifically, the Office of Buildings Energy Research and Development.

The goal of Yankee Engineering's project is to demonstrate a modular design that is compatible with the customer's existing manufacturing infrastructure. This design will significantly reduce start-up costs and provide a basic appliance that can be modified to service several market segments by adding or subtracting pre-engineered modules. The contract terms specify that the engineering sample 1) demonstrate that the concepts can be transferred to a mass-produced appliance that uses gaseous fuels interchangeably, 2) have a seasonal efficiency in excess of 95%, 3) have a sound level of 65 decibels or less, 4) have combined NO_x and CO emissions of 50 parts per million (ppm) maximum, 5) have outputs of 10 to 30 kW (34,000 to 100,000 Btu/hr), and 6) meet a targeted factory selling price of \$395 in 1984 dollars.

The appliance will be based on a single 52-gallon integrated hydronic/potable hot water/active solar heating. A storage and distribution module is fitted with novel stratification and vortex tube-enhanced heat transfer features. It will incorporate state-of-the-art control, sound dampening, insulation and heat transfer techniques and will accept optional hot air, air conditioning and system-powered electric generation and storage modules.

In addition to home heating units, pulse combustion has also been applied to drying processes.^(a) At least two companies (Sonodyne and Sonic Corp.) in the U.S. have commercially applied pulse combustion to drying processes. The Sonic Corporation in Idaho has developed a highly successful method for drying yeast in breweries. The raw material, having a consistency of thick milk, is injected by metering pumps directly into the hot gas (2300°F). Once in the gas, the material is almost instantly atomized into finely divided particles, with most of the moisture converted to steam. The mixture is then blown into a big cyclone (14 ft dia, 30 ft high) where further drying occurs and 80% of the yeast (with approximately 5% moisture left) is taken out. The rest of the yeast is collected in a baghouse.

The pulse combustor is run at maximum efficiency, which is controlled by monitoring off-gas temperature. The operation is continuous (7 days a week),

(a) The original development of this idea is generally attributed to R. Lockwood (1979).

which results in a very consistent quality of the yeast. Daily output is approximately 5 tank trucks. The quality of yeast is claimed to be higher than that of the competition, which uses more conventional drying methods. Because of the fast drying rate, the yeast's nutrients supposedly are retained, whereas they are largely destroyed in the conventional, slower methods.

3.2 PULSE COMBUSTION APPLICATIONS IN DEVELOPMENT

The Gas Research Institute (GRI) currently has the most active role by far in furthering pulse combustion technology (Johnson et al. 1984). It supports R&D work at the American Gas Association (AGA) Laboratories, the Battelle-Columbus Laboratories (BCL), the Georgia Institute of Technology, and at various industrial companies. Specifically, Georgia Institute of Technology is attempting to relate the characteristics of the pulsating gas flame to the design of the pulse combustors. Experimental results, along with the formulation of a computer model, are serving as a starting point for developing a rational design procedure for pulse burners.

In a related project, BCL is characterizing the ignition sources and flow patterns in several pulse burners and is determining the causes for limitations in the burner's operating ranges. The effects of changes in size and configuration are being evaluated to determine principles for scaling pulse burners.

To foster practical applications of pulse combustion, GRI also supports the design and testing of several pulse appliances. Ongoing projects at AGA Laboratories in Cleveland, Ohio, include the development of a residential space heater, residential water heater, commercial deep-fat fryer, and other commercial cooking equipment. To complement these efforts, AGA Laboratories is also advancing the application of pulse combustion systems by investigating burner modulation, sound attenuation, design scaling, and the potential for electric power generation from exhaust heat. Recently, Forbes Energy Engineering, Inc., a firm with experience in pulse combustion equipment design, has been working on applying pulse combustion in commercial space conditioning and water heating. All of the appliances have the potential for near-term commercialization,

and equipment manufacturers are participating in their development. Some of AGA's ongoing projects (supported by GRI) are discussed in more detail in the following sections.

3.2.1 Residential Space Heaters

One example of GRI's support was the successful Lennox G-14 Pulse^{™(a)} central heating furnace (Wilson and Adams 1982), which entered production in May 1982. GRI also initiated an R&D project in 1982 to develop a high-efficiency pulse combustion space heater that would vent emissions to the outdoors rather than release them into the home (Belles and Griffiths 1982; Thrasher 1983). An engineering model of the pulse space heater, designed and built by AGA Laboratories, demonstrated a steady-state efficiency of 93% at a fuel input rate of 18,000 Btu/hr. The next step following this proof-of-concept was to minimize the cost of manufacturing the unit while still meeting requirements for performance, durability, size, noise, ventilation, and condensate disposal.

A prototype production model of the pulse space heater was manufactured by Martin Industries and achieved a steady-state efficiency of 92.9%, which should offer residential gas users a 38 to 50% fuel savings over standard, vented, gas space heaters. An ignitor/sensor control system for this heater was developed by Prestolite. To reduce overall sound pressures to acceptable levels (down to 59 decibels), designers incorporated the following:

1. an air inlet box, lined with sound-absorbing material
2. an exhaust decoupler, which is simply a space that decouples the burner system from the exhaust pipe, thus desensitizing the system to the length of the pipe.

A twelve-unit field test of this pulse combustion space heater began in January 1984 and is continuing. Most of the field test units were placed in occupied residences across the country, with the cooperation of local gas utilities. The heaters were installed either in an area of the home not served by the central furnace or in homes in warm climates where the space heater supplied the primary heat demand.

(a) Trademark of Lennox Industries, Inc., of Texas.

The field test is providing details on the starting and operating characteristics of the heater and demonstration of the heater's safety and reliability and its individual components. Efficiency is being measured before, during, and after the field test, and the amount of gas and electricity consumed by the heaters at the test site is being determined. Other field test information includes data on nitrogen oxides emissions and evaluation of user acceptance.

With good results from the field test, pulse combustion space heater technology should be ready for commercialization by late 1984. Residential applications will include zone heating, supplemental heating along with an existing central system, and area heating for room additions not served by a central furnace.

A recent study projected the average annual potential market for gas-fired space heaters (both freestanding and wall mounted) to be 300,000 to 350,000 units per year through 1988. The study noted that the development of more competitive products, such as pulse combustion models, could improve this market potential by 30% to 40%.

3.2.2 Commercial Deep-Fat Fryer

In May 1983, after more than two years of GRI-sponsored research, AGA Laboratories began operating an engineering prototype deep-fat fryer that incorporates a pulse combustion burner and heat exchanger system. Vulcan-Hart Corporation, a leading manufacturer of commercial cooking equipment, is participating in this research (Griffiths and Thrasher 1982; Farnsworth 1983).

During several months of laboratory tests, the engineering prototype of the stand-alone pulse combustion deep-fat fryer demonstrated efficiencies greater than 80%. The fryer is scheduled to enter field testing in August 1984, with commercialization expected in spring of 1985 (Farnsworth 1984).

3.2.3 Commercial Griddle

Eight manufacturers of commercial cooking equipment are participating in the development of a GRI-sponsored application that is related to the deep-fat fryer. AGA Laboratories is investigating the application of pulse combustion to a heavy-duty (commercial-scale) griddle (Himmel 1983). The major design

challenge in perfecting the cooking surface is to distribute the heat evenly across the griddle's surface. Pulse combustion offers a viable solution to this problem because considerable variation in combustion chamber geometry can be achieved to tailor temperature distribution without disrupting the pulse combustion process. It is particularly important that the temperature be nearly uniform across the cooking surface.

To date, modifications to the combustion chamber design have reduced the maximum temperature difference across a 1-square-foot section from 200°F to below 40°F, which is within the range of many current designs. Further design work will attempt to achieve a more even temperature distribution and determine the interactive effect of two combustion chambers on the surface temperatures at the boundary where two sections join.

Given successful design developments, the sectional griddle should start field tests in October 1984, with commercialization targeted for late 1985. The next step in improving the efficiency of commercial cooking equipment is to extend the griddle technology by incorporating it in a pulse combustion fry-top range, which could be commercialized in 1986.

3.2.4 Residential Water Heater

AGA Laboratories, in another GRI-supported R&D effort, is also developing a residential pulse combustion water heater that would compete with Hydrotherm's equipment. State Industries, Inc., a leading manufacturer of water-heating equipment, has provided input that has been used to reach a final design that is both practical and efficient (Kolodgy and Liljenberg 1982; Kolodgy and Fuller 1984).

During 1982, following engineering model tests, 30- and 75-gallon prototypes of the pulse combustion water heater were tested, and at the request of the participating manufacturer, design work began on a 40-gallon prototype. After this prototype has been sufficiently refined and tested, the residential pulse combustion water heater will begin field tests in November 1984. If test results are successful, the water heater could enter commercial production in late 1985 or early 1986.

3.2.5 Other Pulse Combustion Applications

Encouraged by the initial success of pulse combustion products now on the market, GRI recently initiated two more projects that will incorporate the pulse combustion process in gas-fired equipment. Both are aimed at the commercial sector and are contracted to Forbes Energy Engineering.

In the first project, begun in late 1983, Forbes is developing a high-input water heater that will meet commercial demands of over 3500 gallons per day. Units with these capacities would be suitable for applications in hospitals, commercial laundries, and large hotels, motels, and restaurants. The GRI goal is a minimum recovery efficiency of 90% with stand-by heat losses of about 1.5%.

The targeted field test date for the project is spring 1985. State Industries, Inc., is the equipment manufacturer involved in developing the high-input water heater, which is expected to reach commercialization during 1986. The unit most likely will be manufactured in input capacities of 500,000, 750,000, and 1,000,000 Btu/hr.

In a related project begun in early 1984, Forbes is developing a commercial pulse combustion steam boiler with an efficiency of 86%. The project approach is to design a boiler that is easy to manufacture, yet can substantially improve the space conditioning efficiency of large commercial or institutional buildings. Field testing is scheduled to begin in late 1986, with commercialization the following year. Weil-McLain Company, a major boiler manufacturer, is participating in the development and expects to market the boiler in two sizes, 500,000 and 2,000,000 Btu/hr.

3.3 OTHER KEY OPPORTUNITIES FOR PULSE COMBUSTION APPLICATIONS

In addition to the applications already discussed in Sections 3.1 and 3.2, other applications are also very supportive of ECUT goals. These opportunities were noted at the Pulse Combustion Workshop held in Seattle (Appendix A) and are expanded here. They should be strongly considered for industrial development.

3.3.1 Alternative Fuels

As discussed in Section 3.1, many projects to develop pulse combustion heaters for domestic and commercial application are currently under way (sponsored by GRI). All of these devices are operating on gaseous fuels, mainly natural gas. Domestic space and water heaters of this type are already commercially available (Johnson et al. 1984). Many researchers have demonstrated that pulse combustion can operate also on solid fuels, such as pulverized coal, lignite, wood chips and other low-grade fuels. It even appears that combustion can be more complete for such fuels if they are burned in a pulse combustor. Therefore, many applications could be expected for solid fuel (particularly low-grade fuel) pulse combustors.

3.3.2 Steam Raising and Power Generation

The compactness of pulse combustion devices is a valuable attribute. This compactness would be particularly important for larger versions, such as would be required, for example, in power stations or in generating process steam. As the steam load changed, the number of operating combustors would be changed accordingly.

3.3.3 Chemical Reactors

Another potential area for future applications of pulse combustion is chemical processing in reactors. Because turbulent heat and mass transfer can be considerably increased in a pulsating environment, chemical reactions, which depend on molecular interaction between the participating species, would be speeded up. Calcining processes would probably be the initial applications. For example, pulse combustion has already been successfully demonstrated in lime calcination (Rudolph et al. 1978b). Another possibility would be to apply pulse combustion to catalytic processes in which the oscillating movements of the hot gas environment would increase the rate of interchange between catalytic and reacting particles. To date, this possibility has apparently never been studied. Finally, pulse combustion could be used in coal gasification operations.

3.3.4 Fluidized Beds

Still another potential area of application is pulse combustion in fluidized beds. In recent years, fluidized bed combustion has gained industrial acceptance, even though the development of this relatively new technology is still continuing, particularly for pressurized fluidized beds. The pulsations in the flow can be expected to increase the mixing of the species that participate in the combustion process and thereby effectively improve the mass exchange and the heat transfer within the bed. This should result in a more complete combustion, in a cleaner exhaust and in a more compact facility. Because self-sustaining oscillations probably cannot be generated in fluidized beds, it must be assumed that the pulsating flow has to be artificially generated from the outside, for example, by pulsating the air supply.

4.0 R&D OPPORTUNITIES IN PULSE COMBUSTION

Since the first descriptions of the potential for pulse combustion by Reynst in the 1930s and 1940s, predictions have been made that this new technology would "revolutionize combustion and gasmaking practice" (Steverson 1951). Despite many attempts to introduce pulse combustion on a wide scale, however, it still remains a relatively obscure technology, widely unknown even in industrial circles. Therefore, the barriers to be overcome and the needs for additional R&D work to make pulse combustion more attractive to industry are two main issues. The following two sections address these issues.

4.1 BARRIERS TO DEVELOPING AND USING PULSE COMBUSTION TECHNOLOGY

Several barriers have been identified as hindering the development and use of pulse combustion technology: its noise, a lack of awareness of the technology, lack of design and evaluation procedures, lack of credibility, the higher cost of pulse combustion equipment in comparison to conventional combustors, and lack of an infrastructure to move the technology into the market place. Each of these barriers is discussed in more detail in the following sections.

4.1.1 Noise

The most obvious negative attribute of pulse combustion has been its intense noise (up to 140 decibels). Silencers (mufflers) therefore must be used to reduce the noise to an acceptable level. Much effort has been spent on this problem, and it has been demonstrated repeatedly that with proper design, the emitted noise can be reduced to below 60 decibels. However, this reduction cannot be achieved routinely in any new configuration and usually "cut and try" experiments are required. With increasing experience in this field, general design rules might be expected to evolve, which then would reduce developmental testing considerably. Unfortunately, the current fundamental understanding of the complexities in pulse combustion is still incomplete.

4.1.2 Lack of Awareness

Another barrier in developing and using pulse combustion technology is that the potential of pulse combustion is still largely unknown except for a

few engineers who have a special interest in this field. The most effective way to overcome this obstacle appears to be by introducing actual equipment, as exemplified by GRI's approach of subsidizing the development of various appliances for domestic and commercial use. A similar approach for developing industrial-type pulse combustion equipment might be taken by the government.

4.1.3 Lack of Design and Evaluation Procedures

Reliable mathematical models for design and scale-up do not exist. The common approach for developing a pulse combustor for a specific purpose has been by trial and error. This approach can be tedious, particularly if optimization is required, which is normally the case. Availability of analytical methods to design and evaluate a particular device without extensive testing would be highly desirable. However, the physical and chemical phenomena that comprise the pulse combustion process need to be better understood before these methods can be developed. Understanding these phenomena would require considerable systematic research rather than the previously used ad hoc research.

4.1.4 Lack of Credibility

Because pulse combustion is still generally considered a new, untried technology (even though it has existed for over 40 years), engineers are often still somewhat skeptical about the reliability and durability of pulse combustors, especially those with mechanical valves. For example, except for certain propulsion devices, the aerovalves used in pulse combustion may appear questionable to many people, since aerovalves all deviate more or less from a desirable perfect performance. Because the valves have always been the most critical part in pulse combustors, the reservations are justified. Therefore, only favorable, long-term, practical experience with standard manufactured devices is likely to remove such skepticism.

4.1.5 Higher Cost

Another barrier to introducing pulse combustion has been the relatively high cost of such equipment compared to more conventional combustors. Industry is now trying to reduce the manufacturing costs by adapting well-proven mass production methods. It appears possible that the cost of heating systems can be brought down far enough so that the energy saved in one or two years will

pay for the extra cost of installing a pulse combustor instead of a conventional heater (Johnson et al. 1984). For example, the Lennox residential heating system now appears to be gaining momentum because of its proven high efficiency and quality (Steinberg 1983).

4.1.6 Lack of Infrastructure/Constituency

Engineers in industry perceive the lack of communication among the scientific engineering, manufacturing, and marketing institutions as a major barrier to introducing pulse combustion.^(a) Also, very limited experience seems to exist among the installers of pulse combustion heaters. Yankee Engineering Company has suggested that these entities work together as a team to develop and commercialize not only new pulse combustors but entire pulse combustion systems. Obviously, a combustor by itself has little usefulness unless it is integrated into a well-functioning and compact system, including proper control and safety measures, that has a way of reaching the market place.

4.2 R&D NEEDS

Beginning with Schmidt's original work for the V-1 buzz bomb, pulse combustion repeatedly has been the subject of both theoretical and experimental R&D. However, most of this work has been performed on an ad hoc basis, aimed at a specific device. Therefore, even though a considerable amount of practical experience exists, the fundamental understanding of the pulse combustion process itself is still largely incomplete. In this section, areas where additional fundamental and applied R&D in the field of pulse combustion are needed the most will be discussed. This discussion addresses the technical barriers noted in Section 4.1. Most of the areas discussed are the result of the discussions held at the Pulse Combustion Workshop, as described in Appendix A.

All development work on pulse combustion could best be carried out in close cooperation with industry. This cooperation would assure that R&D work remains closely related to practical aspects, such as ease of manufacturability, long-term reliability, low cost, etc. The current cooperative work

(a) Obtained through telephone conversation with C. Yankee of Yankee Engineering Company, April 1984.

arrangements between AGA and various heating equipment manufacturers, under common GRI sponsorship, could serve as a model.

4.2.1 Development of Analytical Models

A primary goal of fundamental and applied R&D work in pulse combustion would be to advance the state of the art to allow a pulse combustor to be designed for a specific purpose from basic principles, without requiring extensive developmental testing on a trial-and-error basis. Other goals would be to examine new areas in which pulse combustion could be used and ways to optimize existing and new pulse combustion devices.

The phenomena of pulsating flow is extremely complex, especially if it involves heat and/or mass transfer. Fluid dynamicists have therefore only occasionally dealt with it on a strictly fundamental basis [Uchida 1956; Schultz-Grunow 1940; Carrier 1955 and others^(a)]. However, these early efforts (though in some cases already quite sophisticated) were somewhat isolated and did not include modern turbulence theory, which at that time was only in its infancy.

Although not intended to advance pulse combustion technology, a considerable amount of high-quality research on oscillating combustion was performed in the 1960s. At that time, rocket development for the National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD) was plagued with combustion instabilities (Crocco 1968), which in some cases lead to the destruction of rocket engines. The results of this research have apparently only been considered by very few workers in the field of pulse combustion. It appears, however, that a more thorough study of this work could further the basic understanding of pulse combustion. Most likely it would be particularly useful in developing pulse combustors with higher pressure amplitudes,^(b) which in most applications is a very desirable goal. Whereas present pulse combus-

(a) Feldman (1968) gives an overview of the more important papers concerning these early efforts, particularly as they apply to Rijke-Tube configurations.

(b) The commonly used "acoustic approximation" for the analytical treatment of pulse combustion is no longer adequate for higher-pressure amplitudes, and the more complex, but more accurate, "method of characteristics" for non-steady gas dynamic flows has to be resorted to (Schultz-Grunow 1940).

tors operate with only a few psi at the most, the pressure fluctuation in rocket engines sometimes approaches 1000 psi. A similar argument can be made also for fundamental research of other types of combustion instabilities that occasionally occur in industry (Barrere and Williams 1968; Putnam 1971).

A few papers on combustion in the literature are devoted to fundamental phenomena encountered in oscillating combustion (Kilham et al. 1965; Sipowicz et al. 1970; Blackshear and Watt 1984; and others). Again, although the work described in these papers was not intended to further pulse combustion technology, they still provide insight into phenomena that are identical or closely related to those found in pulse combustion. A detailed study of these papers therefore would be worthwhile.

Even without the occurrence of combustion, pulsating flow in pipes and ducts is in itself quite complex, especially if the flow is turbulent (which it normally is in combusting flows). Only recently have fluid dynamicists begun to systematically investigate the important role that turbulence plays in pulsating flows. For example, Ramaprian (1984) extensively reviewed the literature on pulsating pipe flows. Also, a special wind tunnel has been built in which pulsating flows can be experimentally investigated (Borell et al. 1984). So far, of course, combustion phenomena are not included in these efforts. However, the efforts represent a direct approach from which a complete understanding of pulse combustion phenomena that is based on first principles could eventually evolve. It would therefore be useful for workers in pulse combustion to monitor the progress in this particular field of fluid dynamics.

Whereas most of the work cited above is concerned with relatively slow pulsations (<60 Hz), corresponding effects at higher frequencies (up to 1300 Hz) have also been studied (Hill and Greene 1977). So far, however, only experimental results have been obtained, and no attempts have been made to generate an analytical model. Studies of higher frequencies should be continued and an analytical model generated.

Because the general fundamental research described above is necessarily long term, it is not likely to produce immediate tangible results that could aid in energy conservation in the near future. Nevertheless, it is considered to be important enough to be included in current ECUT activities. This was

also the opinion of the participants of the 1984 Pulse Combustion Workshop (see Appendix A). They thought (see Table A.2 in the appendix) that fluid flow and combustion merit priority attention separately as well as interactively. Such work is ultimately hoped to lead to a useful mathematical model for pulse combustion.

4.2.2 Methods of Noise Abatement

Noise levels of pulse combustors must be reduced below a certain level (55 to 60 DBA) before pulse combustors can become more widely acceptable. The workshop participants also saw this need to control noise. The most effective way to control noise appears to be operating two or more phase-synchronized pulse combustors in parallel. Systematic research is therefore required to develop reliable methods to achieve this synchronization. Such work is particularly important for pulse combustion systems operating at higher amplitudes.

4.2.3 Design Methods for Scaling Combustors

R&D is needed to develop a method for scaling pulse combustors so that reliable conclusions can be drawn from model testing at reduced scale. This modeling could then considerably decrease the cost of developing new pulse combustion systems. A review of the literature indicates that scaling apparently has never been adequately addressed, and therefore the need for sponsored R&D work in this field is well justified.

4.2.4 Research on Combustors Using Alternative Fuels

As noted in Section 3.3.1, most existing pulse combustors are fueled by natural gas or other types of gaseous fuels. Experience with liquid and solid fuels is largely limited to research projects that have only demonstrated that such fuels can be burned in pulse combustors. Additional R&D work is now needed to develop pulse combustion devices that can be manufactured at reasonable cost for practical use in industrial or commercial applications. Of particular interest would be pulse combustors for coal not only operating in the "Rijke" but also in the "quarter wave" configuration. The modes of operation of such a combustor need to be investigated because they depend on many parameters, such as size and type of the burned coal, size and frequency of the

combustor, pressure gains, heat transfer characteristics, and exhaust pollution. Attending problems such as ash handling, feed-mechanism for the ingoing coal, and control of output also need to be addressed before a working system for practical use can be assembled. The possibility of feeding coal slurries directly into a pulse combustor has not been examined to date, but appears to have considerable potential.

Many other solid fuels besides coal could be burned in pulse combustors. The low-grade fuels (e.g., lignite, peat, wood) particularly may be burned more effectively in pulse combustion than would be possible in regular combustion. As several experiments and minor applications have shown, liquid fuels (a wide variety of oils) can also be burned in pulse combustors. However, large-scale use of this possibility is practically nonexistent, and additional R&D work is necessary to develop practical systems. The possibility also may exist that a specially designed pulse combustor could be operated on a variety of fuels, for example, gas and oil.

Many liquid and solid wastes are best disposed of by incineration. The inherent higher efficiency of pulse combustion therefore is attractive for these special "alternative fuels."

4.2.5 Research on Pulse Combustion Dryers

Drying is an excellent application for pulse combustion. As indicated in Section 3.1, two companies have commercial gas-fired units for drying yeast. Research is needed to extend applications to other areas. The objective of this research would be to develop prototype drying models. The modes of drying seem to be 1) drying during passage of the material through the resonance tube, and 2) enhanced drying in the acoustic field outside the pulse combustor. Neither has been studied. Information is needed both on the types of materials that can be dried without damage and on the drying rates. Test data should be obtained as a function of time, humidity, frequency, and amplitude.

4.2.6 Systems Analysis Study of Critical Industrial Applications

The lack of awareness, infrastructure, and constituency are barriers that can be initially addressed with a systems analysis study. The objective would

be to identify and describe critical industrial applications where the use of pulse combustion technology would be innovative, energy-efficient, and cost-effective.

Although pulse combustion is now being used in a few commercial applications, it is still largely unrealized in industry, even in industries using combustion in one form or another. Its potential for industrial applications has been largely overlooked or ignored. Pulse combustion was more seriously considered as a viable option only when the steep increase of energy costs about 10 years ago compelled combustion efficiencies to be improved. So far, pulse combustion has been used mainly for domestic and commercial heating. Specifically, several gas-fired furnaces and hot water heaters have been developed in the last few years (largely on GRI's initiative) and are now available commercially. Such pulse combustion furnaces have proven to be highly efficient (as high as 93%), and GRI claims that they can save 30% to 50% in fuel costs. Other applications, such as drying and dehydration, have also been proven to be highly successful.

Such positive results indicate that many industries using heat in one form or another might also conserve a significant amount of energy by using the fundamentally very efficient pulse combustion process. A systematic examination of the entire spectrum of U.S. industries is needed to identify those having the largest potential for significant energy savings from pulse combustion. Cases considered would include power plants, chemical processing plants, external combustion engines, heat treating processes, etc.

Chemical processing has specific potential that should be examined more closely. Many chemical processes require high temperatures to proceed efficiently, i.e., at a sufficient speed and degree of completion. However, the high temperature needs to be present in the system for only a brief instant. In some cases, efficiency can be improved by providing peak temperatures only cyclically, rather than by keeping temperatures constant at a rather high level.

Examining industries for potential energy savings from the use of pulse combustion would involve working with industries and thus would be a first step

in creating a greater awareness. The results of the study would provide information to industry and would therefore be a beginning in developing a larger constituency for pulse combustion technology.

4.2.7 Research on Miscellaneous Pulse Combustion Characteristics Leading to Improved Efficiency

Participants at the Pulse Combustion Workshop mentioned several other relatively important topics that were considered to be poorly understood and therefore require further R&D. For example, operating two or more pulse combustors in parallel or in series is a possibility. Such schemes could lead to ways to substantially reduce the pulse combustor's noise levels, and reducing noise is very important for environmental acceptability. The schemes could also lead to more "highly loaded" combustors, which are generally considered to be more efficient, but unfortunately more noisy.

Another topic requiring additional study is heat transfer in pulsating flows. Knowing the extent to which the heat generated in the combustion process can be extracted and used for a specific end use is highly important for successful applications. Combustion pulsations and heat transfer characteristics are known to be interdependent, but a valid quantitative formulation of this relationship is not yet available.

Finally, a method to optimize the inlet valve has never been satisfactorily developed and therefore also merits continued study. This study would be particularly appropriate for the aerodynamic type of valve for which many configurations have been proposed and tried. It is felt that the largely neglected fluidic vortex valves would provide promising alternatives and should therefore be given special attention.

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APPENDIX A

PROCEEDINGS OF THE PULSE COMBUSTION WORKSHOP

May 23-24, 1984

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INTRODUCTION

This workshop was conducted to obtain input from key professionals in the pulse combustion field. The purpose was to 1) identify applications supporting ECUT goals, 2) indicate the main technical problems, which if overcome, would represent ECUT "breakthroughs," and 3) identify new project ideas for pulse combustion and especially those that are consistent with ECUT goals.

In addition to Dr. David L. Brenchley, who directed the workshop, the following people were participants:

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Each participant was sent a copy of a working paper on pulse combustion. In addition to outlining the needs of ECUT, the paper indicated why their input was important and how it would be used. The participants were asked to review the working paper and make comments on its technical content. They were also

asked to think of new project ideas for pulse combustion research. For each idea they were asked to prepare a write-up describing the idea, listing the problems addressed, outlining the approach, and recommending appropriate follow-on work.

The two-day workshop was structured to focus on applications, technical problem areas and new project areas. The following agenda was used:

WORKSHOP AGENDA

WEDNESDAY, MAY 23

<u>TIME</u>	<u>ACTIVITY</u>
8:00 - 8:15 a.m.	Getting started
8:15 - 8:30 a.m.	Overview of ECUT
8:30 - 9:00 a.m.	Participants check in
9:00 - 10:15 a.m.	Pulse combustion applications
10:15 - 11:45 a.m.	Pulse combustion technical problems
11:45 - 12:00 noon	Morning wrap-up
12:00 - 1:30 p.m.	Lunch break
2:00 - 5:30 p.m.	New pulse combustion projects
5:30 - 6:00 p.m.	Wrap-up

THURSDAY, MAY 24

8:00 - 8:15 a.m.	Focus on Review and Agenda
8:15 - 9:00 a.m.	Problems addressed by new projects
9:00 - 11:30 a.m.	Group discussion topics
11:30 - 12:00 noon	Wrap-up and evaluation

Dr. Branchley maintained the role of workshop facilitator. As the subsequent material reflects, having a facilitator helped the group to keep close to the agenda and be productive. Overall, the participants gauged the

workshop to be successful. More specifically the following evaluation comments were made by the six participants:

<u>Statement</u>	<u>Response</u>			
	<u>Strongly</u> <u>Agree</u>	<u>Agree</u>	<u>Disagree</u>	<u>Strongly</u> <u>Disagree</u>
The workshop was well organized.	3	3		
I had ample opportunity to share my ideas and describe my views.	4	2		
I feel the time spent on this workshop was worthwhile.	1	5		
This workshop was a good way to obtain my input.	3	3		
The workshop facilities were comfortable.	2	4		

The things they liked best about this workshop were 1) interactive aspects, 2) open discussion, 3) interaction with others in the field, 4) limitation to a small number of competent participants, 5) active discussion and interaction with the research community, and 6) meeting fairly informally with other workers.

The things they liked least were 1) not enough time, 2) lack of movie projector, 3) slightly crowded room, 4) some discussion got sidetracked.

PULSE COMBUSTION APPLICATIONS

The results of the brainstorming session on pulse combustion applications are presented in Table A.1. In the discussion following the table, the applications are grouped into three main categories depending on the primary purpose of the device. These main categories are then subdivided further into more specific types, although some overlapping is unavoidable. In the discussion in each category, the specific applications have been underlined for emphasis.

TABLE A.1. Pulse Combustion Applications
(listing is random)

1. Air/Water Heating Immersion Heaters (2)
2. Coal/Lignite Combustors (4)
3. Wood Combustors (1)
4. Heat Exchangers--Heat Transfer (2)
5. Home Heater & Central Heating (1)
6. Dehydration and Drying (2)
7. Fog and Smoke Generation (1)
8. Chemical Reactors -- Example: Calcining in East Germany (5)
9. Coal Gasification (3)
10. Steam Raising (4)
11. Gas Turbines (2)
12. Power Generation (2)
13. Thrust Generation & Conversion to Mechanical Energy (1)
14. Miscellaneous Heat Exchanger Cleaning
15. Catalysis--Increase Effectiveness (3)
16. Gas Generator--Forced--Induced Drafts (1)
17. Electric Generation--EFD--MHD (1)
18. Pulse Fluidized Bed--Mixing Applications (3)
19. Dry Particle Atomizer, e.g., insecticides (1)
20. Particle Agglomeration (Prcleaning of Exhaust Gases)
21. Noise Generator--Crowd Control, Bird Control
22. Sonar Generators--(Navy)
23. High-Temperature Heat Pumps (1)

After generating the application presented in Table A.1, the participants identified the ones that are currently available commercially. Items 1, 5, 6, and 7 were mentioned as definitely being commercial, but there was uncertainty about Items 8 and 13. Each participant then noted the 8 applications they felt were most promising from an ECUT perspective. The numbers in parentheses in Table A.1 reveal how many participants ranked that application as one of the eight most promising. Note that chemical reactors, coal/lignite combustion, steam raising, pulsed fluidized beds, catalysis and coal gasification were thought to be promising applications.

The participants generally agreed that pulse combustors should be used only if they provide a significant advantage over existing technologies. In many cases advantages may not be important enough to justify extensive R&D efforts. On the other hand, in some cases advantages might not be self-evident. Therefore, it was recommended that marketing studies should be done first to determine what the probable pay-offs would be. The drawbacks (such as noise problems) should also be taken into account because, unfortunately, they may become worse if one tries to intensify the pulse combustion process.

Another trade-off point might be the hardware. On one hand, pulse combustion would allow a general reduction in combustor size, but on the other hand, this might entail greater complexity of the hardware.

APPLICATIONS INVOLVING THE HEAT GENERATED BY THE PULSE COMBUSTORS

1. Air/Water Heating

Applications in this category (mainly immersion heaters) are commercially available for home and commercial use. They are predominantly operated on natural gas. To date this is the main application of pulse combustion. (Items 1 and 5 in Table A.1). Presently, the most successful version of a pulse combustor home furnace is being manufactured by Lennox Industries. Pulse combustion boilers for residential and commercial use are offered by Hydrotherm Inc. Other U.S. companies are now also entering the field or are still in the

process of economic evaluation. These commercially available units are actually complete packaged systems (not just the combustors), including enclosures, ducting, controls, etc. Potentially such heaters could also be operated on other fuels (oil, coal, lignite, wood, peat, etc.). These possibilities are indicated by Items 2 and 3.

2. Heat Exchangers

Heat exchangers of the conventional type (Item 4) represent those applications where heat is extracted from the pulse combustor for other (mainly industrial) purposes than domestic air or water heating. More specific examples of such applications are listed under Items 10, 12, and 18. Normally, these applications all require some sort of heat exchanger to extract the thermal energy contained in the hot exhaust gases generated in the pulse combustor and to transfer it to another working fluid (such as steam). The main advantage here is that the pulse combustor automatically provides intense forced convection heat transfer (mostly by the oscillatory movement of the hot combustion gases), whereas conventional combustors usually provide only the less effective induced free convection. The net effect of this feature is that heat exchangers in connection with pulse combustors can be more compact.

Also falling into this category would be the high-temperature heat pump (Item 23), even though practical applications of such a device are not readily envisioned. (Evidently, the heat pump would extract heat from the pulse combustor via a heat exchanger and transfer it to another working fluid, which in turn would be "pumped" to a still higher temperature).

3. Direct Contact Heat or Mass Exchanger

Applications under this category would include most pulse combustion drying and dehydration methods (Item 6) since the wet particulate matter to be dried comes into direct contact with the hot exhaust gases of the pulse combustor. If such matter also undergoes thermal decomposition and/or chemical reactions with the hot gases, the pulse combustor would act as a chemical reactor (Item 8). Such chemical reactions conceivably could be speeded up considerably by

the intense mixing process in the pulse combustor, especially if suitable catalysts are also present (Item 15). Various calcining processes appear to be examples that possibly could benefit from such methods. Coal gasification (Item 9) appears to be worth special mention in this connection.

In the field of drying and dehydration several U.S. companies offer custom-made equipment for various purposes. For example, Sonic Corp. has developed a highly successful operational unit for large-scale drying of brewers' yeast.

Chemical reactors based on the pulse combustion principle have been developed in East-Germany, e.g., for the production of lime and cement. Whether they are available outside the eastern block countries is not known. It might be expected that applications of this type could have a significant impact on the chemical process industry, particularly when combined with suitable catalytic reactors.

APPLICATIONS INVOLVING THE VIOLENT FLUID MOTION GENERATED BY PULSE COMBUSTION

1. The original use of pulse combustion was for thrust generation (Item 13) e.g., for missile, aircraft or helicopter propulsion purposes. Primary examples are the V-1 buzz bomb of WWII and various pulse-jet devices, developed after the war, but which are no longer of real interest.
2. Miscellaneous applications (Item 14) use, e.g., the violent motion of larger particles entrained in a highly turbulent pulse-jet to impact on dirty (e.g. fouled) surfaces for cleaning purposes. The impact of such particles upon each other may break them up in some sort of grinding effect. Fog and smoke generators (Item 7) and particle sprayers would be other examples of this type of application, as would various atomizers listed under Item 19. If the particles contained in the exhaust are very fine (powdery), the opposite effect, i.e., agglomeration to larger particles, may occur (Item 20) so that they could more easily be filtered out. Reportedly, D. Scott of the University of Toronto has demonstrated such effects with high-intensity sound waves and also with pulse combustion, which actually proved to be more effective.

Because pulse combustors can have a very high power density, they can be kept relatively small so that hand-held devices can generate hot gas jets of an intensity and power unobtainable with any other combustion devices of equivalent size. This may be useful for rapid de-icing. Miscellaneous types of such so-called "swing-fire" units have been commercially available for some time from two German firms (Motan GMBH and Espar Eberspacher). Even more highly loaded versions of such devices are now under active development by Kentfield and co-workers. The two German companies also market various types of fog and smoke generators.

3. Because the pulse combustor provides a source of hot exhaust flows, it could possibly be used as a gas flow generator for forced or induced draft flow applications, which are mentioned under Item 16. Potentially this might be used in driving a gas turbine (Item 11). Another potential (though rather remote) application might perhaps evolve in the field of MHD power generation (Item 17), although most likely the presently achievable temperatures are too low for such use. So far, no commercial applications have been reported in this category, but J.A.C. Kentfield is currently involved in testing small-scale pressure gain devices that could eventually lead to gas turbine applications.

Obviously, the chemical reactors (Item 8), already discussed above, could also be mentioned here, since they would take advantage of both the high temperatures and the intense fluid mixing obtainable simultaneously in pulse combustion devices.

APPLICATIONS USING THE INTENSE NOISE GENERATED BY PULSE COMBUSTION

Clearly, in most applications the noise emitted by the pulsating combustion is objectionable. However, in a few applications such intense noise could be turned into a benefit, such as in Items 21 and 22 where intense noise could be used in control of obnoxious bird congregation or of crowds. Because the emitted noise can be made to occur in bursts, it could possibly be used for sonar devices. The intense sound waves (possibly supported by induced structural vibrations) also reportedly have caused desorption of fouling deposits in heat exchangers. Other applications (such as the already mentioned bird scaring) have apparently been used abroad, although no documentation was found.

TECHNICAL PROBLEM AREAS IN PULSE COMBUSTION

Table A.2 contains the results of the brainstorming session on the technical problem areas. In the discussion following the table, these results have been regrouped into four major categories, which represent the main general topics that must be considered.

TABLE A.2. Technical Problem Areas
(listing is random)

1. Fluid Flow (2)
2. Combustion: Gas, liquid, and solid fuels (2)
3. Interaction of flow and combustion (3)
4. Heat transfer
5. Efficiency predictions and estimates
6. Noise levels (3)
7. Combustor configuration
8. Combustor life/reliability (1)
9. Manufacturing methods (1)
10. Design methods
11. Inlet valve design (1)
12. Re-ignition
13. Air pollution emissions (1)
14. Operational safety
15. Instrumentation and controls
16. Types of pulse combustion/applications (1)
17. Turndown ratio (2)
18. Maximum pressure gain (2)
19. Scaling (3)
20. Synergistic effects in combustors (3)
21. Fuel admission systems (1)
22. Catalysis (2)
23. Phase synchronization of multiple combustors (4)
24. Valveless pulse combustion backflow control (1)
25. Flow rectification at inlet (1)
26. Mathematical modeling of pulse combustion using numerical methods (3)
27. Multi-fuel combustors--same unit (3)

After listing these problem areas presented in Table A.2, the participants identified the 8 they felt were most critical from an ECUT perspective. The numbers in parentheses in Table A.2 reveal the results. There was a definite feeling that the basic phenomena of fluid flow, combustion and their interaction effects are not well understood. Mathematical modeling, scaling, and the problem of noise control were also significantly noted. One participant said that because phase synchronization of multiple units (Item 23) was an obvious solution to the noise levels (Item 6), he chose to allocate more of his talks to these two.

INSUFFICIENT FUNDAMENTAL UNDERSTANDING OF THE PHYSICAL/CHEMICAL PROCESSES IN PULSE COMBUSTION

There was a consensus that the basic scientific disciplines underlying nearly all pulse combustion phenomena are fluid mechanics (Item 1) and combustion science (Item 2). Undoubtedly, the flow patterns in a pulse combustor are nonstationary, highly turbulent, and three-dimensional. The flow must be treated as compressible, especially for the more highly loaded devices. Therefore, gas dynamic procedures should be used in treating flows in pulse combustors. The acoustic features, so evident in pulse combustion, can simply be considered here as special topics of fluid mechanics. With the simultaneous occurrence of flow and combustion, two additional major scientific disciplines are entered, namely thermal science and chemistry (specifically combustion chemistry).

Each of the forementioned processes is complex and not thoroughly understood. Yet, in pulse combustion they occur together. Therefore, understanding the basic processes in pulse combustion is particularly complex and difficult (Item 3).

In most practical applications, as much energy as possible must be extracted from the heat source provided by the pulse combustion process. Therefore, problems of heat transfer (Item 4) may also pose substantial

difficulties in specific applications. Again, it has to be remembered that heat transfer by itself is a wide and complex area of engineering that is still not yet fully explored.

The ultimate goal for this first category would be a reasonable understanding of all the synergistic effects (Item 20) within a pulse combustor so that a mathematical model (Item 26) could be developed for a specific application. This then would yield numerical solutions (obtainable by computers) that could be used for predicting (or at least estimating) the overall efficiency (Item 5) of that particular pulse combustor.

OPERATIONAL CHARACTERISTICS

The present knowledge of pulse combustor technology is not so much derived from theoretical studies as from numerous tests and experiments. A fairly large amount of such empirical information has been reported; however, some of that literature is partly contradictory. As a result, it is generally possible to predict the gross behaviour of a pulsating device with some degree of confidence, but there are various specific features that are much less predictable.

In certain applications, it is desirable to maximize the pressure gain (Item 18) to obtain best performance. Several approaches could achieve this, but predicting the effectiveness of such approaches is not yet possible. Intimately connected with this particular problem area is the effectiveness of the flow rectification at the inlet (Item 25), which poses problems mainly with valveless devices (Item 24) since they usually allow a certain amount of backflow. Fluidic devices, which can be used for redirecting the backflow (by 180°) in propulsion applications, are of only limited interest for the ECUT program.

For future applications it would be highly desirable if the same pulse combustors could operate on a variety of fuels (Item 27). This goal appears to

be reachable; however, certain problems exist such as turndown ratio (Item 17) or re-ignition difficulties (Item 12). These difficulties would first need to be explored in more detail. Possibly, catalysts (Item 22) could be a useful tool in this respect. However, so far practically nothing is known about them as pulse combustion enhancers.

Undoubtedly, a major drawback of pulse combustion is normally the emission of noise (Item 6). Various approaches have been tried out (some with good success) to drastically reduce the noise level. One particularly promising approach is using multiple units with their timing (phase) properly synchronized (Item 23). How to achieve such synchronization consistently is still a problem, even though twin units have already been successfully operated.

DESIGN UNCERTAINTIES

Ideally, pulse combustion technology should be developed to such a degree that a pulse combustion system for a specific application could be designed (Item 10) on paper, partly based on a better understanding of the fundamentals and partly on additional practical experience. Such a design, after being built, should then work efficiently without additional development or optimization testing. However, one problem would still be whether such designs could simply be scaled up or down to meet specific requirements (Item 19). Not to be overlooked in this respect are the reliability and the life expectancy (Item 8) for a particular pulse combustor design.

ENVIRONMENTAL ACCEPTABILITY

As previously mentioned, the intense noise (Item 6) developed by many pulse combustors has been a major drawback holding back a more enthusiastic acceptance. In fact, federal regulation may require that the emitted noise be reduced below a specified maximum level. Also not quite clear are questions on exhaust emissions that could be considered air pollutants (Item 13). As in any

combustion device, the specific operating conditions determine the pollutant emissions. They need to be better defined for pulse combustors. Finally, it must be ascertained that pulse combustors can be operated safely (Item 14) and do not in any way constitute a potential hazard to the user. Even though this does not appear to be a major hurdle, the issue has to be addressed.

POTENTIAL NEW APPLICATIONS

Like many new inventions, the pulse combustor has been a seemingly useful device looking for applications. Although some real applications have been established, many more have been explored or were merely proposed. Still others most likely will surface. Apparently it would require a concerted effort to solve the problem (Item 16) that pulse combustion so far has not been more widely used. As a first step in solving this problem, potential new projects in the field of pulse combustion were proposed during the workshop. The following section will list and briefly discuss such projects.

IDEAS FOR NEW PROJECTS

The results of the brainstorming session for ideas for new projects on pulse combustion are listed in random order in Table A.3.

TABLE A.3. Ideas for New Projects

1. Study of scaling--e.g., diameter effects
2. Study of types of emissions using liquids and pulverized fuels
3. More effective aerodynamic valves - fluidics
4. Coupling of multiple combustors in parallel
5. Total energy use of pulse combustion in electro-plating industry
6. Use of pulse combustion as soot blowers in the electric utility industry
7. Development of quarter wave combustor for coal
8. Investigation of relationship between frequency and combustion efficiency
9. New methods to increase pulse amplitude
10. Market survey - find industry data, i.e., numbers of potential applications
11. Valveless carburetor for a (otherwise) valveless liquid fuel pulse combustor
12. Conversion of flow through pulse combustion to shaft horsepower--electrofluid generator
13. Ash handling in pulse combustion (all types of combustors using coal) e.g., particle agglomeration
14. Study of heat transfer process in pulse combustion driers
15. Application of pulse combustion to fluidized beds
16. Cycle-by-cycle (cyclic) variation of performance in pulse combustion
17. Investigation of starting phenomena
18. Thin film nozzle--pneumatic nebulizer (pulse combustion provides energy instead of outside pump)
19. Study of pulse combustion in burning of wood
20. Development of pulse combustion with variable valve timing
21. Study of pulse combustion as chemical reactor--i.e. for calcining or thermal dissociation
22. Study of pulse combustion in coal gasification
23. Auxiliary inlets in valveless pulse combustors--improves turn-down ratio
24. Use of pulse combustion as energy source to increase reaction rates (catalyst effects)
25. Study of effects of pulsations on catalysis
26. Investigation to understand mechanisms affecting pressure gains in pulse combustion
27. Study of dual fuel pulse combustors (for example, gas/oil)
28. Study of valve fatigue to alleviate problems in high-density pulse combustors
29. Extract heat from pulse combustion with heat pipes
30. Study of using pulse combustions in series
31. Study of extended heat transfer surfaces--multiple inlets and tailpipes
32. Mutual supercharging - one pulse combustor to supercharge another
33. Study of pulse combustions using coal slurries

Some of these ideas were written up also, and they are documented in the following section. The 33 ideas are categorized here as an aid in considering their relevance to ECJT goals. The following five categories are used:

- o better understanding of basic phenomena
- o analysis of operational aspects
- o effect of combustor/system geometry on performance
- o effect of fuel type on combustor/system geometry
- o development of industrial applications

Some of the ideas could easily be listed in more than one of these categories. However, in the following discussion they have been listed in the category most relevant to ECJT program activities.

BETTER UNDERSTANDING OF BASIC PHENOMENA

In the previous section on technical problem areas it was noted that many of the fundamental aspects of pulse combustion are still poorly understood. To improve understanding, several research study projects were suggested. However, those listed under this category are already at a more advanced state, i.e., closer to actual applications than the fundamental problem areas mentioned above.

Because a pulse combustor provides an environment of hot gases at a very high turbulent mixing rate, such a condition could be quite conducive for an effective chemical reactor (Item 21). Some reports already indicate that pulse combustors have been used for certain calcining processes. Reaction rates in certain chemical processes possibly could be increased further by using catalysts within the pulse combustor (Item 24). The catalysts themselves might conceivably become more effective (Item 25) by the intense turbulent pulsation that they would be subjected to in a pulse combustor environment. As the intensity of the pulsations is made to increase, all thermal and acoustic effects most likely would be increased accordingly. So

far, however, exactly how the pulsation amplitude can be increased under given conditions is largely unknown. Therefore, better understanding the mechanism involving the pressure gains in a pulse combustion process would be beneficial (Item 20).

ANALYSIS OF OPERATIONAL ASPECTS

Some of the proposed new projects listed within this category extend somewhat into the previous section and could be listed there as well. As already mentioned in Item 26 above, increasing the pulse amplitude (Item 9) appears to be quite important in increasing the effectiveness of certain pulse combustion processes. Conceivably, such an increase could be obtained in various ways, which should be tried out and optimized. Also, an increase in frequency conceivably could have a similar effect up to a certain point. A certain optimum frequency probably exists at which the pulse combustion efficiency reaches a maximum. Therefore, investigating the relationship between pulse frequency and combustion efficiency (Item 8) was strongly suggested.

It has also been observed that the cycles in pulsating combustion are not exactly identical; in fact some low-frequency "beating" effects are known to exist occasionally. Because such cyclic variations are unexplainable to date, a detailed study of such phenomena (Item 16) was recommended. Closely related to such nonuniform pulsations are start-up phenomena (Item 17), which sometimes are drastically different from the full running conditions. Because these highly nonstationary phenomena have not yet attracted much attention, they were recommended for detailed study.

One subject area that has had the attention of investigators from the early beginnings of pulse combustion has been the functioning of the inlet valves. Many variations of mechanical and aerodynamic (valveless) versions have been investigated over the years. However, the interaction between valve action and pulse combustor effectiveness is still poorly understood. Therefore, the influence of valve timing on pulse combustion should be investigated (Item 20), particularly if the valve timing would be varied by external control devices. In the case of mechanical (flapper) valves, their

useful life is compromised considerably (e.g., due to fatigue) as the energy density of the pulse combustors is increased. Studies were proposed to find ways to possibly alleviate such problems (Item 28). Obviously, aerodynamic valves would not have this type of problem, but unfortunately they are often less effective. For such reasons, efforts should be spent on improving the design of such valves. One way that should be investigated is to design a naturally aspirating inlet valve that acts like a carburator to inject and atomize liquid fuels (Item 11). Fluidic valves of the vortex amplifier type should also be investigated further (Item 3). So far, there is very little experience in their application to pulse combustors.

EFFECT OF COMBUSTOR/SYSTEM GEOMETRY ON PERFORMANCE

Many configurations of pulse combustors have been developed and tested over the years. So far their design details are mainly the result of empirically gained information. However, better predicting the results of any configurational changes on performance would be very desirable. A very basic and important aspect of such an objective would be the effect of scaling (e.g., changing the diameters over a fairly wide range) (Item 1). Operating two or more pulse combustors in parallel has been attempted before, mainly with the goal of cancelling noise emission (Item 4). Apparently a successful configuration is not easily obtainable; therefore, additional study of the problem was strongly recommended.

It is not known whether series operation of pulse combustors has ever been attempted. Conceivably, the first relatively small pulse combustor drives the following larger one, etc. (Item 3), similar to the (analog) way one stage in an electronic amplifier drives the next larger one. In that way the last (output) stage can be loaded more heavily without incurring the risk of completely killing the oscillations. The turndown ratio would probably be improved by such a measure also. Another suggested possibility to improve this ratio may consist of the use of auxiliary inlets in valveless pulse combustors (Item 23).

The ultimate objective of a pulse combustor is to allow very efficient energy transfer (heat extraction) within a minimum of space. To improve the transfer's effectiveness, extended heat transfer surfaces in pulse combustors (Item 31) were suggested. An initial thought in this respect was to use multiple tailpipes. Another, apparently untried possibility would be the use of heat pipes that might extend into the combustion chamber itself (Item 29). A special arrangement of pulse combustors might be a closed loop in which 3 or more are supercharging each other (Item 32). In that case, one must make sure that the firing sequence always goes in the same direction. This might be attainable by using fluidic devices.

EFFECT OF FUEL TYPE ON COMBUSTOR/SYSTEM PERFORMANCE

Most of the pulse combustors developed and manufactured today burn natural gas. However, it would also be highly desirable to be able to burn other fuels (coal, wood, refuse, etc.) in pulse combustors since it is likely that low-Btu fuels could be burnt more effectively in such devices than in more conventional combustors. Of immediate interest would be a pulse combustor that could alternately switch to either gas or oil fuels (Item 17). Wood burning combustors would also be of interest (Item 19). Since the early days of pulse combustion, the possibility of burning coal (either as a fine powder or in larger particles) has occasionally been investigated. Recently this kind of effort has been considerably intensified, using primarily the Rijke-type combustor. Other configurations, particularly the quarter wave tube, should also be investigated for such purposes (Item 7). Problems with any of the less clean fuels can obviously be caused by ash generation, fouling, slagging, etc. For such reasons alleviating these problems would be important (Item 13). It was also suggested that the extent to which coal slurries could be burnt in pulse combustors (Item 33) should be determined since this might considerably ease problems of properly feeding in the fuel.

Laws currently require that the noxious emissions from any type of combustor be kept below a certain limit. Therefore, knowing the contents of the pulse combustor exhaust is important. Whereas the problem of unburned hydrocarbon is probably not serious, the possibility of increased NO_x

and SO_x emission cannot be ruled out. Therefore, such questions need to be studied in greater detail (Item 2).

DEVELOPMENT OF INDUSTRIAL APPLICATIONS

As already discussed in the "Applications" section, pulse combustion has been used in various technical areas, and its use has been proposed in many other areas. Although the prospects for such additional use look generally good, some uncertainties remain that should be investigated in greater depth before major efforts are committed to introducing them into the marketplace. The workshop participants suggested the following items for consideration in this category. A systematic screening of potential pulse combustion uses in various industries should be undertaken, along with a market survey, to estimate the potential economic benefits to be gained, particularly concerning energy conservation (Item 10). Examples of such potentially useful applications include pulse combustors in the electroplating industry (Item 5) or pulse combustors as a pneumatic nebulizer (Item 18), which in effect may be similar to already commercially available fog generators. Because the pulse combustor exhaust contains both thermal and mechanical energy, it could possibly be used to drive a turbine, which in turn might generate electric power (Item 12). Although pulse combustor applications already exist for various drying processes, this area could probably be extended substantially and at a faster rate, if the physical phenomena (such as heat and mass transfer) that occur in such processes were known in greater detail. Therefore, a study probing these phenomena was suggested (Item 14).

Because pulse combustors generate "puffs" of gas at high intensity and rather high frequencies (noticeable as intense acoustic noise), they could conceivably be used as soot blowers, e.g., in boilers (Item 6). Similar to using pulse combustors in chemical reactors, they could potentially also be used in fluidized bed combustors (Item 15) and for coal gasification (Item 22). It must be realized, however, that considerable R&D efforts would be required before these last two items could become operational.

PROJECT IDEAS DISCUSSED

All the project ideas in Table A.3 were discussed at the workshop. Each idea was clarified to all participants and the group discussion focussed on its relative importance, relationship to other work and ideas, and some ways the project might be implemented. Certain projects were selected for further group discussion after each participant selected one project idea that particularly interested them. The following projects were selected and discussed:

1. study of scaling, i.e. diameter effects
4. coupling of multiple combustors in parallel
7. development of a quarter wave combustor for coal
13. ash handling in pulse combustion--all types of combustors using coal
27. study of dual fuel pulse combustors (for example, gas and oil).

Ideas 1 and 7 are presented in more detail in the following section.

After this discussion each participant rated all 33 project ideas according to his interest in discussing the idea further, i.e., high, medium, or low. Of the 12 ideas that resulted from that rating, the following four project ideas were chosen and discussed because they represented a focus highly consistent with ECUT goals:

8. Investigation of the relationship between frequency and combustion efficiency
14. Study of heat transfer processer in pulse combustion areas
16. Cycle-by-cycle (cyclic) variation of performance in pulse combustors
33. Study of pulse combustors using slurries.

Ideas 8 and 14 are presented in more detail in the following section.

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RESEARCH PROJECT DESCRIPTIONS

Before the workshop began, the participants were asked to think of ideas for new projects. They were asked to write them down, discuss them at the workshop, and then turn in their notes. They were also asked to write up ideas that were developed and discussed at the workshop. The following material is the documentation of these notes as they were received.

COUPLING OF MULTIPLE UNITS

Description of Idea

A system, already presented by J. Kentfield to A.A. Putnam of Battelle-Columbus Laboratories (22 March 1982) involves use of heavy-current flow rectifiers interconnecting combustion zones of combustors required to fire sequentially.

Problem(s) Addressed

The use of pulsed combustors is normally justified because of forced convection action (as in a generator of a forced draft, for example), improved heat transfer (possibly double that of comparable steady flow) and lastly as a generator for thrust generation or drying purposes. All these actions are enhanced by using highly, rather than lightly, loaded combustors. Noise generation is the great enemy of highly loaded combustors. Sequential operation of multiple units is a key to minimizing noise.

Approach

It could be implemented by analysis and by experimentation--suitable designs of heavy current fluidic elements exist (Kentfield: "Pressure-Gain Combustion 1982, A Review of Recent Progress").

Recommended Follow-On Work

To build a demonstrator unit (e.g., a heater or a gas generator) to demonstrate a superior performance to current standard pulsed--combustor results.

Additional Comments

The inherent advantage of valveless pulsed combustors will be more apparent with highly loaded units than is the case with lightly loaded units. In the writer's view, the benefits of the proposed work could be of GREAT IMPORTANCE AND BENEFIT to the field of pulse combustion.

MARKET SURVEY

Description of Idea

An attempt to focus researchers' attention, and that of likely sponsors of research, on the market penetration, to date, of pulsed combustors. This is not a small job; no "breakthrough" will result, but it will help to clarify the picture.

Problem(s) Addressed

To set up an approximate matrix of uses of pulsed combustors versus approximate number of units supplied, or expected to be supplied, in the fairly near future.

Approach

The suggested approximate matrix can be set up, with the help of those of us meeting at Seattle, without additional funding, in the space of about 1/2 hour. Accuracy is not being aimed for, just a general picture. The writer can help, but the help of other participants is vital.

Recommended Follow-On Work

To report the results to DOE in PNL report and, indeed, to others.

Additional Comments

The type of matrix is roughly as follows:

APPLICATION	NAME OF BUILDER	NO. OF UNITS (TO DATE)	
		GUESS	ACCURATE
Air Heaters		?	
Water Heaters		?	
Hand-Held Heater		40,000	
Fogging Units		100,000	
Gas-Generators			
Etc.			

(Perhaps an extra column regarding type of unit (e.g., valved/valveless) would be good.)

VALVELESS CARBURETOR FOR AN (OTHERWISE) VALVELESS LIQUID-FUELED PULSED-COMBUSTOR

Description of Idea

The idea has already been illustrated on at least two previous occasions by the writer:

Kentfield: "Pressure-Gain Combustion 1982, A Review of Recent Progress"
(1982)

Kentfield: "Pulsed Combustion: Promising Areas for Further Research" (1979)

(Both the above papers were presented at the Combustion Institute, Western Canada Meetings, Banff, Alberta, Canada).

Problem(s) Addressed

An attempt to simplify and improve the reliability of highly loaded (valveless) liquid-fueled, hand-held pulsed combustors for use in very cold climates.

Approach

Essentially by testing carried out on existing hand-held 500,000 Btu/hr (150 kW) thermal output pulsed-combustors. This work is surely best carried out by the writer or by a graduate student working under his supervision.

Recommended Follow-On Work

Demonstrate a completely valveless carburetted pulsed combustor. It must be admitted, however, that a successful result would help only a few specialty users.

Additional Comments

The technology to perform the suggested task is, it would seem, almost in place. What is needed is (hopefully) a task within the capability of a single graduate project. See: Kentfield: "A New Light-Weight Warm Air Blower for Rapidly Pre-Heating Cold-Soaked Equipment" (ASME paper 77-WA/HT-20, 1977).

HEAT TRANSFER IN HIGHLY OSCILLATORY VELOCITY FIELDS

Description of Idea

Fundamental work in heat transfer in closed ducts with velocity fields representative of pulse combustors. This study should involve both analytical and experimental work.

Problem(s) Addressed

Hopefully identify and define engineering relationships which predict the heat transferred in such a closed duct.

Approach

Experimentally a long cylinder equipped with a motor driven, piston capable of recreating a respectable representative flow field.

Recommended Follow-On Work

Add combustion.

Additional Comments

More fundamental work of this nature is needed.

MECHANISMS FOR LOW NO_x PRODUCTION IN PULSE COMBUSTORS

Description of Idea

Define the mechanisms responsible for the low NO_x production in pulse combustors. This investigation should include a coupled effort between experimental and chemical kinetic modeling. The experiment should be designed to supply sufficient information for model verification. (For example, high-speed-temperature and species measurements, as well as phase-locked measurements.)

Problem(s) Addressed

NO_x and scaling.

Approach

Use state-of-the-art laser diagnostics for the measurements.

Recommend Follow-On Work

Investigate different fuel types and the effect fuels have on the temperature and species measurements.

DEVELOPMENT OF A PULSE COMBUSTOR WITH VARIABLE VALVE TIMING

Description of Idea

In current mechanically valved pulse combustors, the valve timing is a dependent variable. One idea is to develop a pulse combustor with active valve timing based on electronic feedback from the combustion process. Some previous pulse combustion units have used active valves, but there was no provision for feedback.

Problem(s) Addressed

Variation in valve timing of fuel and air has been effective in controlling emissions from and improving performance of internal combustion (IC) engines. This approach may be more suitable to liquid fuels--the result would be somewhat like fuel injection for an IC engine.

Approach

Breadboard the sensor and control system along with an existing mechanically valved pulse combustor.

Recommended Follow-On Work

Reduce the breadboard design to something more "industrial."

NO_x FROM PULSE COMBUSTOR FIRED WITH LIQUID AND PULVERIZED SOLID FUELS

Description of Idea

We have ample proof that a gas-fired pulse combustor produces low NO_x. Pulse combustors fired with liquid and solid pulverized fuels have potential in the market, but nothing is known about the amount of NO_x they produce. It may be that the NO_x from fuel nitrogen is not affected by pulse combustion, but on the other hand, there might be an appreciable NO_x reduction. We certainly should investigate.

Problem(s) Addressed

The basic problem is to determine NO_x production by typical liquid-fuel-fired and solid-fuel-fired pulse combustion.

Approach

Build two designs of pulse combustors that fire liquid fuel and two that fire solid pulverized fuel. Fuels containing two or three different levels of fuel-bound nitrogen would be fired in these units, and the NO_x output determined along with the usual values of CO, CO₂, O₂.

Recommended Follow-On Work

If either or both the liquid or solid fuel firing showed low levels of NO_x, the next step would be to push for development of application units.

TUBE CLEANING WITH PULSE COMBUSTORS (SOOT BLOWER)

Description of Idea

The Russian literature indicates a use of pulse combustion for tube cleaning in at least two modes: (1) shaking the tube bank, and (2) blasting the tubes. Diamond Power has built air-driven sirens for that purpose, but has not continued with it.

Problem(s) Addressed

1. How effective are the devices against real world cleaning--slag deposits, other deposits?
2. What are the economics?
3. What is the most effective manner of use?

Approach

1. Literature review of existing industrial practices.
2. Theoretical investigation of soot blowing in general.
3. Experimental evaluations.

Recommended Follow-On Work

Feasibility study.

DRYING WITH PULSE COMBUSTION

Description of Idea

Drying appears to be a natural for pulse combustion. The noise one is usually fighting is helpful. Two modes of drying seems to be involved: (1)

drying during passage of the material through the resonance tube, and (2) enhanced drying in the acoustic field outside the pulse combustor. Neither have been studied effectively.

Problem(s) Addressed

The problem is two-fold. First, what materials can fall through the pulse combustor without scorching or deteriorating and second, what is the rate of drying? Beyond the pulse combustor, one might study the problem using fans and acoustic horns and warm air, as an example.

Approach

1) A pulse combustor (mechanically valved for control) pointing vertically downward would be used to drop various materials through; material would enter at various points and the results analyzed. 2) Materials would be dropped through a box enclosing a sound field and hot gases, and the results analyzed as a function of time, material, humidity, frequency, amplitude, etc.

Recommended Follow-On Work

Following this work, the information would be used to produce prototype drying models to test on prospective materials selected on the basis of the data obtained.

Additional Comments

Lack of this information appears to be holding up pulse combustion development in a large potential market.

MORE EFFECTIVE AERODYNAMIC VALVES

Description of Idea

Many types of aerodynamic valves (of the nonreturn type) have been tried out to reduce the amount of backflow from pulse combustors; however, they were

only modestly successful. Surprisingly, the most obvious choice for such purposes, the fluidic vortex amplifier, has only found very limited attention. In a 1973 paper, Syred and Tippetts of the University of Sheffield described some tests in which such a fluidic device has been used in a pulse combustor with turndown ratios as high as 12:1. It might be worthwhile to pursue this idea further since the performance of valves is crucial for the efficiency of pulse combustors.

Problem(s) Addressed

Most aerodynamic valves used in pulse combustors have only a rather modest increase in back-flow resistance (sometimes less than a factor of 2). The higher this resistance, the better the performance of the pulse combustor. Thus, vortex amplifiers (originally developed for fluidic applications) might represent a considerable improvement.

Approach

As a first step, the results reported by Syred and Tippetts should be verified in new tests. Thereafter, vortex amplifiers should be incorporated into a typical pulse combustor and performance improvements should be determined based on detailed measurements.

Recommended Follow-On Work

Devices should be tested in other versions of pulse combustors and should be optimized for each application. Results should be made known to industry.

Additional Comments

It has to be expected that operation of a vortex amplifier consumes some energy (mainly to cover friction losses by the vortex).

EXPLORE WHAT PULSE COMBUSTION PRINCIPLES COULD BE APPLIED TO IMPROVE ENERGY EFFICIENCY OF CHEMICAL REACTORS

Description of Idea

In the same way as the heat transfer can be increased by the oscillating movements of combustion gases, the mass transfer, as it occurs in chemical reactions, could also be increased by the same mechanism. After all, heat and mass transfer are closely correlated.

Problem(s) addressed

Physical and chemical kinetics involved in pulse combustion and simultaneous chemical reactions should be studied. This is a highly complex problem, so far incompletely understood. Most of the basic work in this field has been done abroad.

Approach

Study those attempts in more detail which have already been tried, e.g., calcining, coal gasification, etc. Basically, this requires the consideration of multi-phase flow in the pulse combustor, a poorly understood subject. Such studies could be aided now by modern diagnostic techniques (e.g., laser-based instrumentation). So far, most pulse combustion work has been done with gaseous fuels. But even for these technically simpler cases, laser diagnostic tools have practically never been used for studying the flow and combustion processes in pulse combustors.

Recommended Follow-On Work

Systematically examine chemical reactions (particularly those that are highly energy intensive) which may potentially benefit from such a scheme. Build small pilot plants (test stands) to try out and optimize the process.

Additional Comments

Work in this field would also benefit other applications of pulse combustion such as drying, coal gasification, etc.

APPLICATION OF PULSATING COMBUSTION TO FLUIDIZED BEDS

Description of Idea

The overall effectiveness of fluidized bed combustion (FBC) could possibly be increased considerably in the pulsating mode, as compared with the steady-state mode. It might be unlikely, however, that pulsations would be self-sustaining so that they would have to be generated artificially, e.g., by pulsing the air supply.

Problem(s) Addressed

Does it pay in terms of overall energy conservation to use artificially generated pulsations since their generation in itself involves some energy onsumption?

Approach

Instead of feeding fuel and air on a continuous basis, feed them periodically in short bursts.

Recommended Follow-On Work

After studying related work in this field, small test facilities should be set up to experimentally verify the idea.

Additional Comments

There are already some indications that this scheme might work. For example, it has been observed that fluctuating flames in fluidized bed combustion can result in gas bubbles (volatilized fuel, air, and combustion products) oscillating back and forth within the bed, and that a highly turbulent churning flow may also occur. Bywater and Chung (1983) have shown theoretically (AIChE 29:396) that such movements improve combustion efficiency. Javanovic has provided some experimental observations. Experiments at Aerojet (1983) have also shown that intense acoustic oscillations (artificially generated) also increased volumetric heat release by a factor of 3, improved the combustion rate and increased the turndown ratio. According to the workers in the field, such methods (which are not strictly pulse combustion but closely related), especially if they can be controlled, might also lead to practical benefits in achieving more complete (and thus more efficient) combustion.

In the Soviet Union tests with pulsated fluidized bed furnaces have already been carried out (Rassudov 1983). A comparison of steady and pulsating fluidization (with the same mean flow rates) has demonstrated a reduction in carryover, the free board becoming clear and local discharge of particles almost ceasing and the motion of the bed being of a "piston-like nature".

In this country the idea also has been proposed several times. For example, Lockwood has mentioned it, and apparently A.D. Little has made a study.

DIRECT EXTRACTION OF HEAT FROM COMBUSTION CHAMBER AND PULSE COMBUSTION IN SERIES

Description of Idea

As already pointed out by Reynst, the extraction of heat from the combustion chamber assists in producing the negative pressures of the

combustion cycle. Accordingly, in order to increase the negative amplitude, more heat should be extracted directly from the combustion chamber. This should have a positive effect on the overall efficiency of the pulse combustor.

Problem(s) Addressed

Since pulse combustors are rather small devices with high-power density, there is always the problem of heat transfer through limited surface areas. This could be overcome to some extent by sustaining relatively high-temperature differentials across those limited areas. Such temperatures are present in the combustion chamber itself.

Approach

The proposed scheme could be accomplished, e.g., by placing heat pipes into the combustion chamber. However, pulling too much heat out might stop the pulsations altogether because the return wave might not be able to generate a high enough temperature to ignite the new charge. But this possibly could be overcome by a spark plug (which would have to be there anyway for initial startup), which could be fired in phase with the pulsations. To determine the right moment for firing a pressure pickup (transducer) with the attending control circuitry would probably be required. The power used for such a control device would be very low, as would the cost for the additional instrumentation.

Recommended Follow-On Work

It may prove to be possible not to have to rely so much on self-resonant pulsations, but to enforce such pulsations from the outside by various means. Higher harmonics could be generated in this way; i.e., the shape of the waves need not be purely sinusoidal. Ultimately, one could imagine that shock waves instead of sound waves would travel back and forth in the resonance tube.

Additional Comments

Quite generally, if one extracts energy from a self-resonant system, the feedback mechanism (which generates the oscillations in the first place) is disturbed so that the oscillations become weaker and ultimately die out. In analogy to electric oscillators, it might be feasible to use two or more pulse combustors in series. The first (smaller) one merely acts as an oscillator/driver to set up the oscillating flow, whereas the second (larger) one acts as a power amplifier, which then allows substantial amounts of power to be withdrawn without disturbing the original feedback mechanism.

FIND NEW METHOOS TO INCREASE PULSE AMPLITUDE

Description of Idea

The effectiveness of pulse combustion tends to increase if the pulse amplitude is increased. In particular, combustion efficiency and heat transfer rates could be improved in this way.

Problem(s) Addressed

In many cases pulsed combustion may represent an improvement over steady combustion, significant enough to apply it in a practical application.

Approach

There are many potential approaches which might result in increased pulse amplitudes, e.g., increased feedback, use of a torus configuration, use of periodic fuel injection, use of multiple spark plugs to force ignition (i.e., do not rely on self-reignition), use free pistons instead of flapper valves, and use of less viscous gases, etc.

Recommended Follow-On Work

Higher amplitudes generally result in a higher noise level, which is highly undesirable. Therefore, (new) ways have to be found to decrease that noise.

Additional Comments

It would be desirable if the proposed ways of reaching higher amplitudes could first be analyzed theoretically before building any test devices. However, our present understanding of pulse combustion is not complete enough to do this. This points out the need for more indepth theoretical work.

FIND WAYS TO GENERATE HIGHER FREQUENCIES

Description of Idea

Heat transfer from the hot gas of a pulse combustor to a heat exchanger surface can be improved by faster movement of gas in the thermal boundary layer. Theoretically, this could be accomplished by higher amplitudes and/or by higher frequencies.

Problem(s) Addressed

Better heat transfer is one of the more important characteristics of pulse combustion. However, it is still widely unknown how variations in the operating parameters influence the heat transfer rates. There have even been reports that, under certain conditions, heat transfer may even be diminished.

Approach

Since resonant (fundamental) frequencies of common pulse combustors are rather low, it might be attempted to generate higher harmonics internally. It

also appears possible to impress such higher harmonics from the outside (artificially), e.g., by acoustic transducers.

Recommended Follow-On Work

Because higher frequency noise can more easily be suppressed, it might become easier to sound-proof the pulse combustion equipment.

Additional Comments

It would be less difficult to evaluate this idea if we had a fuller understanding of the details connected with the pulse combustion process. In any case, it might be expected that generation of higher frequency would require some additional energy. Whether in the end there is an overall increase in efficiency remains to be seen.

SCALING OF VARIOUS PULSATING COMBUSTORS THAT BURN VARIOUS TYPES OF FUELS

Description of Idea

At present it is not clear how the characteristics of various types of combustors change, as they are scaled up or down. Consequently, the dependence of various fundamental processes upon scale and frequency (which may change with scale) needs to be investigated. More importantly, the dependence of the interaction among these fundamental processes upon scale should be investigated.

Problem(s) Addressed

This will enable the design of pulse combustors having different capabilities and acceptable performance.

Approach

These problems should be investigated both theoretically and experimentally for the Rijke and quarter wave type combustors. A preliminary, analytical evaluation of the expected dependence of the various processes and combustor performance upon scaling should be undertaken.

Recommended Follow-On Work

Analytical scaling problems should be followed by experimental validation studies.

Additional Comments

The scaling problems will provide the background required for developing large-capacity, practical pulsating combustors.

DETERMINE THE FUNDAMENTAL MECHANISMS RESPONSIBLE FOR DRIVING QUARTER WAVE AND RIJKE PULSE COMBUSTORS

Description of Idea

To attain pulse combustion, the pulsations driving processes must overcome the system's dissipative processes. In spite of our ability to build pulsating combustors, a clear understanding of the fundamental driving process is lacking. Such understanding needs to be acquired to eliminate the costly "cut-and-try" approaches used to date in developing pulsating combustors.

Problem(s) Addressed

Two or more problems: Consider the driving mechanisms in the quarter wave and Rijke type combustors for gaseous, liquid and solid fuels. For each

combustor/fuel combination, this study will have to consider the interaction/feedback between the feed systems/combustor and tail sections flow, and the combustion process.

Approach

Identify various processes/mechanisms believed to be major contributors to driving of combustor pulsations and conduct theoretical and critical experimental studies which will check the driving capabilities of the investigated processes.

INVESTIGATE THE USE OF QUARTER WAVE (I.E., SCHMIDT TUBE) PULSE COMBUSTOR IN THE BURNING OF PULVERIZED COALS OF VARIOUS TYPES

Description of Idea

The suitability of the above type of combustor for the combustion of various types of pulverized coals needs to be determined. Areas to be investigated include the following: relationship between optimum size and frequency of the combustor, and the size and type of burned coal; the performance of the combustors in terms of the combustion efficiency, excess air required, combustion intensity, heat losses, heat transfer characteristics, pressure gains, pollutant form, etc.; dependence of performance upon preheating of air and fuel; determination of optimum design of coal and our feed systems; determination of whether flapper aero valves should be used; and determination of whether a forced flow combustor should be used.

Problem(s) Addressed

It would develop a highly efficient, coal burning combustor for industrial applications and possibly, later on, for utilities. It would encourage

people/industry to replace combustors, which burn premium fuels with those which burn coal, thus saving premium fuels. It may result in a more efficient and less expensive combustor which will reduce capital investment and operating costs.

Approach

It will require theoretical and experimental studies of the performance of the suggested combustor. Also, theoretical and experimental studies of various fundamental heat, mass and momentum transfer processes under oscillatory flow conditions.

Recommended Follow-On Work

The suggested research is a multiyear program.

Additional Comments

We need a multiyear, carefully planned program. Emphasis is on careful planning.

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