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**Japanese Industrial Research
on Lean Combustion:
A Case Study**

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R. A. Hutchinson**

August 1987

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SUMMARY

In recent years, Japanese automakers have introduced a number of successful lean-combustion engines. These engines, in addition to the general expertise in building small cars, have made the Japanese automobiles into the gas mileage champions of the U.S. market. The lean-combustion engines also provide very satisfactory performance and acceptable emissions. United States automakers and research managers, who were probably better informed about lean-combustion than the Japanese were, actively investigated lean-combustion but did not develop an engine.

This report examines the basis for the Japanese innovations, the research that took the Japanese past the U.S. state of the art to permit engine development. A preliminary review of recent (1980s) Japanese literature did not turn up strong evidence of new research activity in the lean-combustion area, but did provide background on new engines developed by several major manufacturers. Developments by the most important automaker in Japan, the Toyota Motor Company, were then chosen for a case study. The study was conducted solely through the Japanese and U.S. published literature, with emphasis on early research conducted in the 1970s. Particular attention was paid to combustion chamber research, notably work which addressed the effects of turbulence and swirl and of prechamber combustion. All these techniques are used in Toyota's lean-combustion engines.

References to early research conducted by Toyota engineers show a heavy reliance on information provided by previous work in the United States. This reliance appears to be characteristic of all Japanese work at the time of lean combustion in automobile engines. Rather than begin with the concept of lean combustion and proceed through stages of research that eventually led to engine designs, Japanese researchers apparently evaluated the more promising options reported in the international literature and then began developmental work on the selected options.

By tracing subsequent publications from particular research and development (R&D) groups, it is possible to view the development of various lean-combustion engine components. In the case of Toyota's prechamber combustion

design, the turbulence generator port (TGP), the evolution of the design and changes to optimize performance and emissions levels can be seen in the Japanese literature. Even more clearly traceable are the stages that led to Toyota's development and selection of a helical intake port and a swirl control valve (SCV) for swirl generation. This arrangement was used in both the central injection engine and the Toyota lean-combustion system that were described in engine announcements published in 1984 (Shiozawa et al. 1984, Matsushita et al. 1984, Takeda et al. 1984).

Despite the successful results, Toyota's research typically involved little more than standard engine tests, Schlieren photography, and some hot-wire anemometry. More fundamental research, resembling that supported by the U.S. Department of Energy, did not begin to occur systematically until the late 1970s and early 1980s. This research primarily involved work breaking in more advanced research tools with little relationship to engine developments at that time.

This report presents an example of how Japanese research progress can be examined by reviewing the Japanese research literature. Although useful information was obtained by this method, it is still difficult to get a complete picture. When reviewing the literature, as was done for this report, one must remember that the marginal use of references by Japanese researchers obscures prior work, as does the tendency of the Japanese to publish several articles on similar or identical topics.

Japanese researchers also actively publish in the international literature, and on occasion, articles are published in English before they are published in Japanese. This publication schedule complicates interpretation of this survey's results, especially with low-quality translations of titles and abstracts.

Japanese publication habits have changed over time. In the 1970s, higher quality and prestige were attached to the international combustion literature. At that time, Japanese publications primarily reported near-commercial development work and product performance test results. The Japanese literature has improved significantly since then, reporting applied and even fundamental research.

Difficulties are also encountered when one examines present and future developments in Japan. Japanese firms often work on several "angles" of a given problem at once, making a narrow, journal-based search difficult. If the literature reviewer has sufficient expertise on the topic in question, results can be encouraging. More Japanese materials are becoming available in English than ever before. Paying attention to the Japanese developments as reported in their literature is becoming feasible, worthwhile, and important.

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1.0 INTRODUCTION

A number of lean-combustion engines have been introduced by Japanese automakers in recent years. These engines have excellent gas mileage, satisfactory emission levels, and strong performance, factors that have made Japanese cars very popular in the United States.

One of the key reasons for the Japanese engine development effort was the emission regulations that were put into place in the early 1970s in the United States. When the move toward such regulations began in 1967 and 1968, the top four Japanese automobile manufacturers at the time (Toyota, Nissan, Mitsubishi, and Toyo Kogyo) joined Ford, oil companies, and European auto companies in the Inter-Industry Emission Control (IIEC) program (Kaneko, Kuroda, and Tanaka 1971). Toyota, Nissan, Mitsubishi, and Toyo Kogyo became very active in research on exhaust gas recirculation (EGR) systems, thermal reactors, various catalyst systems, and other component approaches to emissions problems. Honda, an automaker which was not in the IIEC, pursued a separate path of integrated engine research (Yagi, Ishizuya and Fujii 1970) despite considerable skepticism and ridicule from within Japan (Ohmae 1982). The result of this research, the Honda CVCC engine, was very successful (Date et al. 1974; Yagi, Date and Inoue 1974). The ensuing competitive pressures and the demand for continued or improved fuel economy after the oil embargo of 1973 and 1974 led Japanese and American researchers into active engine development.

The U.S. automakers and research managers investigated lean combustion actively but did not develop production lean-combustion engines. Before the Japanese developments in the 1970s, the U.S. researchers were considered to be far better informed than the Japanese about the phenomena of lean combustion in engines. Observers have questioned what the basis for the Japanese innovations was. What research took the Japanese past the U.S. state of the art in combustion to permit engine development? To answer this question, the Energy

Conversion and Utilization Program (ECUT) of the U.S. Department of Energy (DOE) commissioned the Pacific Northwest Laboratory (PNL)^(a) to examine past Japanese research literature.

A preliminary review of recent Japanese literature, performed by PNL with the assistance of the Global Competitiveness Council, did not reveal strong evidence of new research activity in the lean combustion area, but did provide background on new engines developed by several major manufacturers. An effort was then made to study developments by the most important automaker in Japan, the Toyota Motor Corporation. This study is the subject of this report and was conducted solely through the published literature, with emphasis on early research conducted in the 1970s. The study focused on the research that determined the early stages of lean-combustion engine development. Particular attention was paid to combustion chamber research, notably work which addressed the effects of turbulence and swirl or prechamber combustion. All these techniques are used in Toyota's lean-combustion engines.

1.1 SCOPE AND APPROACH

The initial set of papers used in this study were selected from those identified in a preliminary PNL investigation with assistance from the Global Competitiveness Council (Rubinger and Wiener 1985). These papers described several types of lean-combustion technologies. During this study, the articles that either described or clearly affected lean-combustion work at Toyota were emphasized. References in these articles which discussed or led to early research on lean combustion were selected and reviewed; then the selected articles' references were reviewed. This process of selection and review was continued until 1) no further references were given, 2) all of the references were not Japanese, 3) the references were not relevant, or 4) the references could not be acquired. Very few articles fell into the last category. Finally, the principal journals in which the reviewed articles were published were also scanned to uncover seemingly related work that was not referenced.

(a) Pacific Northwest Laboratory is operated for the DOE by Battelle Memorial Institute.

All the articles were reviewed for their principal findings and the extent of technical data provided. Partial translations were performed to clarify these points. Particular attention was paid to articles which provided experimental data from work related to lean combustion.

A possible shortcoming of this methodology is that the technology development (rather than research) orientation of the initial papers may have prevented discovery of all of the original lean-combustion research. The general scanning of key journals was designed to alleviate this problem; a few articles of interest were uncovered. Because of the study's focus on one particular manufacturer in a field where little basic research was done in Japan outside the universities, the data set used may be relatively complete.

The combustion research uncovered in this study is discussed in Section 2.0. Section 3.0 contains a general review of Japanese journals relevant to internal combustion engine research.

2.0 LEAN-COMBUSTION ENGINE RESEARCH

This chapter discusses activity on prechamber combustion and swirl, which appear to have been the key areas of lean-combustion research at Toyota. The prechamber combustion work includes the development of the turbulence generator pot (TGP), used on some of Toyota's lean-combustion engines. Discussion on swirl includes development of the helical port and swirl control valve (SCV), also used in Toyota's engines. The primary question addressed, however, is whether Toyota did any more fundamental work that guided these developments.

Four other areas are briefly mentioned: 1) additional experiments in related fundamental research, 2) analysis of cycle-to-cycle variation, 3) development of a knock sensor, and 4) experiments with a single compression machine. The connection of these areas with research on the process of lean combustion is not direct, and their roles in Toyota's successful engine development are probably small.

2.1 PRECHAMBER COMBUSTION

Research on prechamber combustion in engines has a long though perhaps device-oriented history; a U.S. article illustrating a variety of prechamber combustion designs (Turkish 1974) showed that patents and descriptions of such designs have existed in the United States and Europe since the 1920s. Toyota's work on the TGP appears to have followed this trend of application-specific research. Toyota's initial contributions in this area are discussed first, then the experiments conducted are discussed in detail. Finally, related work at other institutions is mentioned.

2.1.1 Turbulence Generator Pot

In 1976, researchers from Toyota published their first international article on prechamber combustion (Noguchi, Sanda and Nakamura 1976); another article on this technology was published in Toyota Engineering (Toyota Gijutsu) (Sanda et al. 1976a) and reported identical findings. The prechamber in which ignition occurred and from which a jet flame emerges into the main chamber was called the TGP. A sketch of the TGP is shown in Figure 2.1. The research described in these articles was not fundamental; instead, the general effects

FIGURE 2.1. Schematic of a Turbulence Generating Pot Attached to an Engine Cylinder (Noguchi, Sanda and Nakamura 1976)

of the TGP on engine performance characteristics such as specific fuel consumption, misfire rates, and exhaust emissions were reported. Experiments were also conducted on varying the jet flame speed emitted from the TGP and on positioning the spark plug in the TGP.

The references given in both the Toyota Engineering article (Sanda et al. 1976a) and the Noguchi et al. (1976) article in the SAE Transactions are largely by non-Japanese researchers. The references from Sanda et al. (1976a) are shown in Appendix A; only 3 of the 12 references were in Japanese; 4 references were by Japanese authors but were published in English. The Noguchi article (in English) had no references in Japanese. In their international articles Japanese authors seldom reference Japanese language articles but include internationally published work by Japanese authors. The references given address lean combustion, engine design, NO_x formation, emissions modeling, etc.

The TGP work at Toyota does not appear to have been primarily based on earlier activities in fundamental or directed-basic research. Instead, the

researchers relied heavily on the pool of international literature, with particular emphasis on U.S. literature. Researchers at Toyota progressed directly to applied research, confirming the overall effects of the TGP and experimenting with its design to empirically optimize parameters such as the location of the spark plug, the air/fuel mixture, and the direction and strength of the flame torch. The publication of this work at Toyota, as determined within the limits of this study, was in the U.S. literature. This reinforces the emphasis on the use of international journals by the Japanese for their early research.

2.1.2 Additional Details on Toyota Experiments

The earliest experiments Toyota reported were relatively standard engine tests to verify the general influence of the TGP on engine performance: fuel consumption, misfire limits, emissions levels, etc. Subsequent articles described experiments that tested the effects on performance of various design parameters, such as spark plug location, TGP orifice size, the angle of injection from the orifice, and the injection stream speed. Most of the experiments were performed with standard engine test equipment and well-known experimental techniques. These techniques included Schlieren photography, ion gap measurements of flame front propagation, and pressure indicator diagram analysis. A computer model of emissions was also developed. Descriptions of a number of Toyota's experiments, particularly those that focus on improving the TGP design, follow.

In the mid-1970s, experiments were conducted in which the speed of the jet flame spouting from the TGP into the main chamber was varied (Sanda et al. 1976a; Noguchi, Sanda, and Nakamura 1976). Through Schlieren photography, the researchers observed that flames which travelled at very high speeds could not propagate to the mixture around the orifice. The speed gradient between the flame and the mixture was too steep to allow ignition. Further, flame propagation in the main chamber was observed to start when the jet flame reached the top surface of the piston, which also occurred after a reduction of speed.

Another early experiment involved varying the position of the spark plug in the TGP (Sanda et al. 1976a; Noguchi, Sanda, and Nakamura 1976). Researchers found that if the spark plug was placed inside the TGP some of the fuel-air mixture could spout into the main chamber as unburned gas, and the gas

around the spark plug would be poorly scavenged. These effects led to increased misfire with lean mixtures. Misfire was minimal when the spark plug was placed at the TGP orifice. The effect of plug position on the lean misfire limit is shown in Figure 2.2. The extent of the protrusion of the spark plug into the orifice was also varied. The ability to scavenge residual gas was again the principal cause of misfire at the various plug positions. The effect of plug position on the lean misfire limit is shown in Figure 2.3.

In December of 1976 Sanda and Inoue (Sanda et al. 1976b) reported visualization experiments to observe the progress of combustion in the TGP in a conference preprint; a paper was published the next year. The main purpose of these experiments apparently was to provide information for a computer model of combustion and emissions, particularly NO_x emissions.

Also in 1977, researchers reported experiments with the strength of the ignition arc and the duration of the spark in attempts to extend the lean misfire limit (Konishi et al. 1977). The experiments were standard engine

FIGURE 2.2. Effect of Spark Plug Position in the Turbulence Generating Pot on Lean Misfire (Noguchi, Sanda, and Nakamura 1976)

FIGURE 2.3. Effect of Spark Plug Position on the Lean Misfire Limit (Noguchi, Sanda, and Nakamura 1976)

experiments using ion probes and thermocouples to detect misfire. Increasing the arc current was seen to extend the misfire limit providing for the ignition of leaner mixtures. Increasing the spark duration was also found to increase the misfire limit by enabling more complete propagation of the flame. The results of these experiments are shown in Figures 2.4 and 2.5.

In 1978, a more detailed description of experiments to reduce NO_x using the TGP was published (Konishi et al. 1978); a version in English was published the following year (Konishi et al. 1979a). The experimental apparatus consisted of standard engine testing equipment. The results of the experiments were used to verify and adjust a computer model of emissions. Work on the emissions model was again reported in 1978 (Sanda et al. 1978) with adjustments made for observed heat transfer processes. The model predicted less cycle-to-cycle combustion variation when using the TGP rather than the conventional design. This was verified in engine tests. Toyota researchers also published a discussion on moisture mechanisms based on their previous ignition experiments (Kobayashi et al. 1978).

図5 アーク電流が失火限界におよぼす影響

FIGURE 2.4. Effect of Spark Strength on the Lean Misfire Limit (Konishi et al. 1977)

In 1979, additional experiments on varying the speed of the flame emitted from the TGP were reported (Nakamura et al. 1979). Researchers found that fuel consumption could be reduced by reducing the jet flame speed (and thus the engine's cooling loss). However, the jet flame also affects torque fluctuation and NO_x emissions, and these advantageous effects needed to be preserved. This was achieved by not allowing the jet flame to reach the cylinder wall.

Later in 1979, experiments on the influence on torque fluctuation resulting from the TGP were reported (Konishi et al. 1979b). The researchers again used flame photography, pressure history analysis, and ion gap measurements. They concluded that TGP allowed both a shorter ignition delay time and faster combustion. This effect of TGP is illustrated in Figure 2.6.

図6 アーク時間が失火限界におよぼす影響

FIGURE 2.5. The Effect of Spark Duration on the Lean Misfire Limit (Konishi et al. 1977)

2.1.3 Other Research on Prechamber Combustion

Shortly before the first Toyota articles were published, researchers at Nissan published an article in English discussing research on a similar engine, the torch ignited engine (Sakai et al. 1974). The experiments were general engine tests of performance and emissions to prove Nissan's conceptual design. This work was used as a reference by Toyota researchers (as shown in Appendix A, Figure A.1) but no work by any Japanese researchers was referenced by Sakai et al. (1974).

2.2 SWIRL

Research on swirl in engines, particularly that conducted by Toyota, can be traced clearly through the literature, a few years after work on prechamber

図11 着火遅れと燃焼期間

FIGURE 2.6. Effect of the Turbulence Generating Pot on Ignition Delay and Combustion Duration (Konishi et al. 1979)

combustion began. This section outlines the evolution of research on swirl in engines at Toyota; discusses the Toyota experiments in detail; and summarizes research at other institutions.

2.2.1 Swirl Research at Toyota

In the late 1970s, articles from Toyota researchers appeared that indicated a serious effort to investigate swirl. In March of 1979 Inoue et al. (1979a) published an article describing differences in combustion patterns between mixtures with and without swirl. These experiments were conducted with a constant volume combustion bomb with pictures taken via laser Schlieren photography. A similar technique had been used in a Toyota effort (by the same research group) studying the effects of EGR on combustion in engines. This effort was described in an article that was published in English (Nakanishi et al. 1975). The 1975 Nakanishi paper had only one Japanese reference (in English) on gas flow measurement, written by one of the coauthors, Ohigashi of

Kyoto University (Ohigashi, Hamamoto, and Tanabe 1969). Another basic paper, on swirl in diesel combustion, was published in English by Ohigashi, Hamamoto and Tanabe 1971.

In July 1979, the first article (Inoue et al. 1979b) that described applied swirl experiments was published in Toyota Engineering. Curiously, a similar article had been published two years earlier in English (Matsumoto et al. 1977). The July article (Inoue et al. 1979b) did not reference the March 1979 combustion bomb study (Inoue et al. 1979a) but mentioned the 1975 EGR study (Nakanishi et al. 1975) and the 1971 diesel swirl study (Ohigashi, Hamamoto and Tanabe 1971). All of the references were in English or German, and six of nine references were non-Japanese articles (see Appendix A). These references were for papers that discuss swirl, EGR, fluid mechanics, engine control, and exhaust system measurements. Regardless of publication dates, Toyota researchers focused heavily on the global literature for their ideas on swirl, and relied on simple experiments in this early work. Engines with cylinders designed to induce swirl and squish were assembled and tested to view the overall effect on emissions and fuel economy. These experiments suggested that the design with both swirl and squish resulted in the best fuel economy and the lowest level of emissions, particularly NO_x emissions.

Toyota researchers progressed to experiments that were conducted to judge the effectiveness of different means of inducing swirl. In particular, swirl induced by a helical port was compared with swirl induced by a shroud valve; the helical port proved to be preferable. Toyota subsequently developed and evaluated an intake system using a helical port and an SCV. The combination was designed to address the conflicting requirements of increased swirl generation for improved combustion efficiency, while maintaining a high volumetric efficiency. This arrangement of a helical port with an SCV is the current choice for use with the fuel-injected central injection engine and the premixed lean-combustion engine.

2.2.2 Additional Details on Toyota Experiments

Toyota swirl research included at least one piece of basic research and also referred to some previous activity to develop flame photography methods to assess charge dilution via exhaust gas recirculation. Straightforward, applied

research soon began using flame photography and pressure indicator diagram analysis, plus hot-wire anemometry testing of gas motion in various engine geometries.

Inoue et al. (1979a) authored the principal basic research paper (by Japanese researchers) that was referenced in Toyota's articles on swirl. The lead author also became the principal author on the Toyota swirl articles. The experiments described treated premixed gas combustion in a constant volume combustion bomb. Gas motion and flame propagation were visualized using laser Schlieren photography. Three flow states were observed: 1) stationary gas, 2) swirl, and 3) turbulence with mean flow. Effects on pressure rise and combustion time were examined through varying the ignition timing, ignitor position, and gas composition. The effects are shown in Figures 2.7 and 2.8.

図8 乱れの減衰が燃焼時間におよぼす影響

FIGURE 2.7. Effect of Swirl and Ignition Timing on Combustion Period (Inoue et al. 1979a)

図10 点火位置が燃焼時間におよぼす影響

FIGURE 2.8. Effect of Swirl and Spark Position on Combustion Period (Inoue et al. 1979a)

The experiments described in Toyota's first applied article (Inoue et al. 1979b; Matsumoto et al. 1977) were apparently aimed at confirming the effects of squish and swirl in an internal combustion (IC) engine. Four chamber designs were tested at three compression ratios. The chamber designs were conventional open chamber, squish, swirl, and swirl and squish. Conducting the tests on a 1.6-liter 4-cylinder engine, the investigators measured differences in fuel consumption and differences in emissions between the designs. The combination of squish and swirl yielded the best fuel economy and the lowest emissions of unburned hydrocarbons (HC). No analyses of the actual squish or swirl processes were reported. The results can be seen in Figure 2.9. After experimentally verifying the beneficial effects of swirl on combustion, Inoue's research team evaluated the effectiveness of different methods for generating swirl. Two methods, swirl induced by a shrouded valve and swirl induced by a helical port, were compared in an article published in 1980 (Inoue et al.

図21 各燃焼室のHC濃度排出過程

1,600rpm—5 kgm, 空燃比: 14.5, MBT, EGRなし

FIGURE 2.9. Effect of Squish and Swirl on Hydrocarbon Emissions (Inoue et al. 1979b)

1980). In observing the progress of the flame front across a section of the cylinder, the researchers noted that although combustion time was shorter with the shroud valve, the pattern closely resembled that of combustion with a conventional inlet port. The combustion pattern, however, was observed to change and progress more quickly across the region of the exhaust port. This change can also be seen in Figure 2.10. The faster progress of the flame front in this fashion was considered to be important for its influence in restraining knock.

Researchers also compared the overall progress of the flame front with the changing piston crank angle with shroud valves, helical ports, and straight ports. Combustion was completed most quickly in the case of the shroud valve. The researchers noted, however, that this might be because of the presence of minute quantities of turbulence and not resulting from the swirl.

図7 単筒エンジン実験のための供試燃焼室およびポート形状

図8 各燃焼室の火炎伝播パターン (1,200rpm WOT $A/F=13.5$ 点火時期 3° BTDC)

FIGURE 2.10. Propagation of the Flame Front: a) Straight Port, b) Shroud Valve, and c) Helical Port (Inoue et al. 1980)

They concluded that this difference between the shroud valve and helical port cases was small, and that the determining difference was in the pattern of the flame front propagation.

In the third report by Toyota, published in 1983 (Inoue et al. 1983), the researchers describe the effect on combustion of a helical port with the addition of an SCV, shown in Figure 2.11. The purpose of the SCV was to create more air movement, particularly around the center axis of the cylinder as shown in Figures 2.12 and 2.13. Figure 2.14 shows the faster propagation of the flame front across the cylinder with the SCV added. Flame photography was used to track the flame front and hot-wire anemometry was used to clarify the motion of the gas.

2.2.3 Other Research on Swirl

Research on swirl in internal combustion engines appears to have been underway at universities in Japan since the early 1970s. Professor Hamamoto of

FIGURE 2.11. Schematic of a Helical Inlet Port with a Swirl Control Valve (Inoue et al. 1983)

図10 シリンダ内流れ模様

FIGURE 2.12. Schematic of In-Cylinder Flow with the Swirl Control Valve and with a Helical Port (Inoue et al. 1983)

Kyoto was quite active in the area throughout the 1970s. He was a coauthor on an article in English on swirl in diesels in 1971 (Ohigashi, Hamamoto, and Tanabe 1971). In a 1976 paper, a number of other articles published from 1971 to 1974 by Japanese researchers were references for Hamamoto's investigation of swirl induced by a shroud in an intake manifold (Hamamoto et al. 1976). Hamamoto continued his experimental and modeling work, but apparently the diesel paper mentioned above served as the primary reference for Toyota engineers.

Nissan and Mitsubishi Motors and other Japanese manufacturers have been investigating the effects of swirl on combustion in internal combustion engines. Nissan published an SAE Transactions article in 1977 on 4-cylinder engine tests to determine the effect of intensified swirl and squish. This work contained references of a variety of papers from Japanese university

図8 シリンダ内流速パターン (定常流)

FIGURE 2.13. Cross-Sectional Flow Speed with the Swirl Control Valve and with a Helical Port (Inoue et al. 1983)

図6 火炎伝ばパターンのトレース結果

FIGURE 2.14. Propagation of the Flame Front with 1) a Straight Port, 2) the Swirl Control Valve Open, 3) the Swirl Control Valve Closed, and 4) a Helical Port (Inoue et al. 1983)

researchers, including Ohigashi and Hamamoto, as well as U.S. research papers. By 1980, Nissan researchers were looking at swirl phenomena in detail. A conference paper discussed studies of induction swirl using water and a transparent cylinder (Yanagihara et al. 1980). An English-language version of this paper was published in 1981 (Hirotoimi et al. 1981).

Mitsubishi published work on EGR in English in 1975 (Kaneko, Kobayashi, and Komagome 1975) that was referenced in Toyota papers, but appears to have focused more strongly on stratified charge and mixture turbulence than other manufacturers (Nakamura et al. 1978). In general, work by other manufacturers was generally not referenced by Toyota researchers' papers.

In the late 1970s other means of inducing swirl besides helical ports and SCVs were being described by Toyota laboratories. One method is through the use of a turbulence-generating mixture accumulator placed in the cylinder head (Nohira et al. 1980). This design allows higher compression ratios and improved combustion at light loads but requires additional compression work for the accumulator. A second method developed at the Toyota Central Research Laboratory comprised a stratified charge engine with an auxiliary chamber that induced swirl along the main cylinder wall (Oshima et al. 1978). This design was termed "Coronal Combustion Process" (CCP). General engine experiments (i.e., measurements of exhaust emissions, or photographing the combustion process) were conducted. The experiments revealed the potential for reduced HC, CO, and NO_x in comparison with a conventional design.

2.3 OTHER RESEARCH - FUNDAMENTAL AND RELATED STUDIES

Toyota research that is not directly traceable to lean-combustion engine developments is briefly mentioned in this section. This work was uncovered by the same means as the swirl and TGP work, by examining the references of recent papers on lean-combustion engines at Toyota and scanning the relevant journals. The research includes work on fundamental studies, cycle-to-cycle variation, knock sensors, and a single-compression machine. It is included here simply to provide a sampling of Toyota's recent longer-term work. Many other topics are noted in Appendix B.

A few articles authored by Toyota researchers that described basic research were uncovered. However, the link to the applied and developmental work, that is, the link to the experiments with engine swirl or prechamber combustion, are not clear. These articles were not referenced in the articles describing swirl, the TGP or any other developmental work. The articles include descriptions of gas reaction studies through molecular beam gas sampling, preliminary CARS (coherent anti-Stokes Raman spectroscopy) laser diagnostics research, and the development of a transparent piston engine.

In 1979, Toyota researchers reported the development of a molecular beam gas sampling system to study high-speed gas reactions (Fujitani et al. 1979). The device was designed to allow the measurement of many chemical species and unstable intermediates. The device also allowed high-time resolution (50 microseconds) and only required a small gas sample, leaving the source virtually undisturbed. The researchers also attempted to trace changes in the concentration of combustion products and reactants, although problems with accuracy remained. Sketches of the apparatus, the methods of measurement and some initial results were provided in the article. The list of references for the article showed an extensive review of both international and Japanese literature.

In 1981 researchers from the same Toyota group published an article describing some initial CARS experiments (Inoue et al. 1981). The article included sketches of the equipment arrangement. The experiments described, however, were conducted on a standing flame and were directed primarily at learning how to use the CARS setup.

A third development described at about the same time was a transparent piston engine to observe combustion processes and mixture flow within the cylinder (Takizawa, Takahashi, and Matsubaru 1980). The single-cylinder engine used a transparent quartz piston crown which allowed viewing up to 2000 rpm. The article described the engine's design in some detail and also presented preliminary results from testing three different combustion chambers: hemispherical, hemispherical with a TGP, and hemispherical with two spark plugs. The results are shown in Figure 2.15.

図16 各種燃焼室の火炎伝播状況

FIGURE 2.15. Flame Propagation in Cylinders Using a 1) Hemispherical Combustion Chamber, 2) Hemispherical Chamber with a TGP, and 3) Hemispherical Chamber With Two Spark Plugs (Takizawa, Takahashi and Matsubaru 1980)

2.4 INDICATED MEAN EFFECTIVE PRESSURE ANALYSIS OF CYCLE-TO-CYCLE VARIATION

Between 1978 and 1980, researchers from Toyota reported on an investigation of the causes of the cycle-to-cycle variation of combustion. The first two papers introduced methodology: a relational equation for variation, defined as variation in indicated mean effective pressure (IMEP) (Ishiyama et al. 1978), and an overview of the experimental apparatus used (Kononji, Toda, and Ishiyama 1979). The variance of released heat and of change in internal energy were separated, and released heat correlated with certain fuel system characteristics and variance in internal energy with certain combustion characteristics. In the third paper (Ishiyama, Toda, and Motomi 1980a), pressure diagram measurements were used to examine factors affecting mixture uniformity, including EGR, ignition timing, swirl ratio, and combustion chamber configuration. Factor effects occurring in the early stages of combustion were

separated from those occurring in the later, main stage. A final paper (Ishiyama, Toda, and Motomi 1980b) examined the effects of atomization of injected fuel and intake manifold temperatures on combustion variation using the now-established methodology. Journal articles discussing this work overlap with the preprints referenced here and are listed with the preprints. They give the mathematical model and the experimental results in some detail.

2.4.1 Knock Sensor

In the late 1970s work was underway at Toyota to develop a trace knock sensor for use in production engines. Early experiments with a piezoelectric sensor were reported in 1979 (Imaizumi et al. 1979); a more complete description of the sensor that was developed was presented in 1981 (Ota et al. 1981). The description of the device, as well as mechanical and thermal performance and reliability tests, were reported in some detail in this later article. However, since the knock sensor is not directly related to research on lean-combustion processes, the review of the development of the knock sensor was not pursued further.

2.4.2 Single Compression Machine

In 1982, the use of a single compression machine (SCM) for use in combustion tests was described by Toyota researchers (Iwashita et al. 1981; Hattori et al. 1982). This machine was not unlike a device developed a few years earlier in the United States (Wong, Rife, and Martin 1978). Using the device the researchers conducted experiments on variables affecting ignition. These included the type of spark plug, the compression ratio, and the flow velocity of the mixture. The experiments conducted with the SCM focused on the presence or lack of ignition, rather than the process of ignition, hence this research was not pursued further in this study.

3.0 REVIEW OF JOURNALS AND PUBLICATIONS

In studying lean-combustion developments through the Japanese literature, some journals were of more use than others. This chapter briefly discusses the relevant literature in terms of quality and availability. There are subtle differences between Japanese and American journals as well, but those have not been analyzed here. Although Japanese researchers in the engine combustion field actively publish in international publications, especially those of the American Society of Automotive Engineers, a substantial body of literature is not translated. For announcement of significant developments such as work on a new engine type, new carburetor, etc., the international literature is very useful in reporting Japanese progress. However, the Japanese literature more fully reports incremental developments in technologies and research, such as fundamental research, before that research attains international significance. Therefore, for some types of research, the Japanese literature can provide earlier information. Because Japanese articles in international literature often do not reference Japanese articles at all, a skewed picture of what is happening in Japanese engine research is likely to result if systematic attention is not given to Japanese articles.

Japanese publications on spark ignition (SI) combustion have noticeably improved over the past 15 years. For example, 10 years ago Internal Combustion Engine (Nainen Kikan) was dominated by articles describing product developments and commercial advertisements. Today, this publication has evolved into a professional journal featuring a mixture of technology development articles, as well as articles describing more fundamental investigations of engine and combustion processes. This journal seems to contain the best mixture of good technical articles in this field in Japan.

Similarly, Toyota Engineering (Toyota Gijutsu) was little more than a product announcement 15 years ago. Ten years ago, more substantive technical papers began to appear, and today the papers presented feature a mixture of research articles and technology development work. Both Internal Combustion Engine, and Toyota Engineering would be good general sources for American engine researchers to review periodically.

Perhaps the best sources for timely information, however, are the pre-prints of scientific lectures of the Jidosha Gakujutsu Koenkai Maezurishu, which includes early versions of most publications of the Japanese Society of Automotive Engineers (JSAE). Many of these are also seen eventually in two other principal JSAE publications: Transactions of the Society of Automotive Engineers (Jidosha Gijutsukai Ronbunshu) and the Journal of the Society of Automotive Engineers of Japan (Jidosha Gijutsu). Selected articles from these are translated for the JSAE Review.

These journals and others are briefly reviewed, based on the type of article that the publication attracts (e.g., product description, technology development, fundamental research of processes, etc.); the typical level of technical detail provided in the articles; the type of authors that publish in the journal (e.g., university researchers, company researchers, etc.); and the amount of English provided in a typical article. The English given, however, may be very rough; for this study retranslations were done on a number of occasions.

Because not all of the publications have selected English names, the Japanese names are given first. If the English name is concurrently published, then it is also underlined. If the English name is only a translation of the Japanese name, it is enclosed with quotation marks.

Nainen Kikan (Internal Combustion Engine) contains articles ranging from descriptions of research on engine processes to descriptions of the performance of nearly commercial technologies. This journal is possibly the best regular publication in this field. Over the past 10 years the quality of the articles has steadily improved. Typically, the articles contain a fair amount of experimental data and performance test data, although not to the extent found in purely technical, research-oriented publications. The authors are industry and university researchers. English titles and abstracts are provided with each article. The journal is published monthly, and is abstracted in Japanese Technical Abstracts.

Although the articles in Toyota Gijutsu (Toyota Engineering) are limited to research at Toyota, and all of the authors are affiliated with this company, the publication contains a collection of good technical papers. The articles

tend to report applied developments, but fundamental investigations are also reported frequently. Performance and experimental data are usually reported in some detail, similar to that seen in Nainen Kikan (Internal Combustion Engine). English titles and abstracts are usually provided. The journal is published monthly and is listed in Chemical Abstracts and Automobile Abstracts.

Jidosha Gijutsukai Ronbunshu (Transactions of the Society of Automotive Engineers of Japan) is probably the best of the JSAE technical publications. The articles are well presented with fair technical detail. Articles translated in the English language JSAE Review are typically taken from articles in the Transactions. Researchers from a variety of industrial organizations, research centers and universities publish in these transactions. Developmental, applied, and fundamental research are reported with experimental and performance data. The transactions include English titles and abstracts, and are listed in Japanese Technical Abstracts.

Jidosha Gijutsu (Journal of the Society of Automotive Engineers of Japan) tends to contain articles that describe developmental work. Resembling a trade journal, the articles presented tend to emphasize technology developments and performance information. The other JSAE technical publications tend to present articles that present more technical detail. The journal is published monthly, and English language titles and abstracts are included. It is listed in Japanese Technical Abstracts and Automobile Abstracts, among others.

Articles in Jidosha Gakujutsu Koenkai Maezurishu ("Preprints to Scientific Lectures of the Society of Automotive Engineers of Japan") are similar to those presented in Jidosha Gijutsu Ronbunshu. Because these articles are preprints from a conference, often in hand-printed form until recently, they are not as polished as the journal articles. These articles also may not be as well screened as those in the transactions. Researchers from the industry, universities, and research centers are represented in this publication. This publication is issued twice a year, contains no English, and is not currently indexed by any Western abstracting or indexing service.

The Bulletin of the Japanese Society of Mechanical Engineers contains articles that describe a range of experiments in mechanical engineering. The experiments tend to reflect fundamental investigations of processes or

phenomena, making this a much more scientific journal than automotive-related publications listed previously. The Bulletin of the Japanese Society of Mechanical Engineers is an English language publication comprising selected articles of already published in Transactions of the Japanese Society of Mechanical Engineers. The Bulletin is widely available in the United States, but because of translation time there is an 8-month lag in publication. Approximately one fifth of the articles are published in the Bulletin. Articles related to engine combustion appear periodically. The Bulletin is published monthly with each issue containing 40 to 50 articles.

Nihon Kikai Gakkaishi (Journal of Japanese Society of Mechanical Engineers) contains a variety of articles ranging from technology descriptions to new briefs to editorials. It is similar in format and detail to the Mechanical of Engineering Magazine of the American Society of Mechanical Engineers. Occasional papers relating to new engines and engine technologies are presented, but experiments are not reported in much detail. This journal is issued monthly, contains English titles, and is listed in Applied Mechanics Reviews, Chemical Abstracts, and Copper Abstracts.

Nihon Kikai Gakkai Ronbunshu, Series B (Transactions of the Japanese Society of Mechanical Engineers) contains papers that describe detailed fundamental investigations in thermodynamics and heat transfer. The articles are similar in detail to those published in the Bulletin of the Japanese Society of Mechanical Engineers however this series is more topically focused and many more articles are published. This publication is issued monthly, contains English titles and abstracts, and is listed in Chemical Abstracts, Copper Abstracts, Japanese Technical Abstracts, and others.

Jidosha Kenkyu ("Automobile Research") is a small publication reporting the activities of the Japan Automobile Research Institute. The articles tend to be short and technically general. This publication is issued monthly, contains English titles, and is not currently indexed by an abstracting service.

Toyota Chuo Kenkyujo (Toyota R&D Center) contains fairly detailed publications of projects at the Toyota R&D Center. The papers span a wide range of technical activities that are relevant to the manufacture of automobiles, hence

combustion-related articles appear only occasionally. This publication is issued monthly and contains English titles.

Other major journals that contain articles on engine combustion, which have not been reviewed, are

- Fuel and Combustion Engineering (Nenryo oyobi Nensho)
- Nissan Technical Review (Nippan Giho)
- Nippon Kekan Technical Report (Nippan Kokan Giho).

Many other university and industry journals are also published; all the above publications and others are now abstracted by Japanese Technical Abstracts; some are also in Chemical Abstracts.

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APPENDIX A

REFERENCES CITED IN EARLY ARTICLES AT TOYOTA
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FIGURE A.2. References from Inoue, T., et al. 1979. "The Effects on Combustion Chamber Design and Compression Ratio on Emission, Fuel Economy and Octane Number Requirements." Toyota Gijutsu 20(1).

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OUTLINE OF PAPERS FOUND IN COMPUTER SEARCH
OF 1980 TO 1984 TOYOTA PUBLICATIONS

APPENDIX B

OUTLINE OF PAPERS FOUND IN COMPUTER SEARCH OF 1980 TO 1984 TOYOTA PUBLICATIONS

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(2 versions)

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Analysis of the Knock Phenomenon Using Rapid Compr. and Expansion Machine

Anal. of Flame Loss Mech. in a Lean Mixture; Effect of Ignit.

Electric Power

Spark Ignition of Flowing Combustible Mixtures

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Meas. of Engine Combust. by TV - Spatial Dist. of Flame Front Surface

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Production of a Sideview Engine

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Constant Volume Combustion Chamber With Prechamber

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