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High temperature Air Combustion

From Energy Conservation to Pollution Reduction

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Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

High temperature air combustion : from energy conservation to pollution reduction / authored by H. Tsuji … [et al.].
p. cm. -- (Environmental and energy engineering series)
Includes bibliographical references and index.
ISBN 0-8493-1036-9 (alk. paper)
1. Combustion engineering. 2. Environmental protection. I. Tsuji, H. (Hiroshi) II. Series.
TJ254.5.H54 2001
621.402′3—dc21 2001043860

International Standard Book Number 0-8493-1036-9
Library of Congress Card Number 2001043860
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

Dedication

Ryoichi Tanaka
March 29, 1928–Oct. 17, 1997

This only book on the subject of "high temperature air combustion: from energy conservation to pollution reduction" is dedicated to the late Ryoichi Tanaka, President of Nippon Furnace Kogyo Kaisha Ltd, Yokohama, Japan from April 12, 1950 to the time of his death on October 17, 1997. Tanaka dedicated his entire career to promoting the development of advanced industrial furnaces that are today known as the most efficient and environmentally benign. He made pivotal contributions to the practical application of high temperature air combustion principles for use in advanced furnace design by introducing most efficient regenerators. He was a patient educator to professionals in the field, a good colleague, an outstanding mentor and friend to members of his staff, a fine, talented, and intellectual individual, and an extremely generous friend. He promoted the art and science of high temperature air combustion that continues to gain good recognition in the technical community. His dedicated efforts during the 1990s on advanced smart industrial furnace design are now providing the fruits of his efforts, and are being utilized worldwide, including Japan, Asia, Europe and the United States.

Tanaka was born on March 29, 1928 in Nagoya, Japan. After graduating from Tohoku University in 1953 in economics, he started the operation of his Nippon Furnace Kogyo Kaisha Company. He began to participate in the social and business activities related to his company at the very early stage of his career. He was appointed as a director of the Industrial Furnaces Association in 1959, a former organization of the Japan Industrial Furnace Manufacturers Association (JIFMA), and was then appointed as vice-chairman of JIFMA in 1966. He was also appointed as director of the Japan Industrial Furnace Manufacturers Pension Foundation and then president in 1991. He founded the Japanese Flame Research Committee (JFRC) for the International Flame Research Foundation (IFRF, Netherlands) in Japan and served as the chairman of JFRC starting in 1977. In 1992 he was installed as the president of JIFMA and was then appointed as director of the energy conservation center, Japan, in the same year. He was appointed as vice president of IFRF in 1994. He received many prestigious honors and awards, including the Blue Ribbon Medal Award in 1986 and the Social Achievement Award of the Japan Society of Mechanical Engineers in 1995.

This book, as well as the development of high performance industrial furnaces, was one of the goals and a vision of Tanaka to enhance industry–university exchange as well as international exchange of combustion technologies. Members of the technical community value his commitment to and accomplishments in this remarkable technology of significant energy savings, downsizing of the furnace, uniform thermal field, and pollution reduction, all of which occur simultaneously.

Foreword

This book represents the outcome of the collective efforts of many scientists and engineers from industry and academia. The Japan Industrial Furnace Manufacturers Association (JIFMA), under the sponsorship of the New Energy and Industrial Technology Development Organization (NEDO), initiated a new High Performance Industrial Furnaces development project during 1993 to 1999. The goal of this project was to demonstrate significant reduction in energy consumption in the industrial sector. This major undertaking by the Japanese government involved many Japanese companies and organizations and some academic institutions. These research and development efforts have resulted in numerous technical publications, reports, mass media publicity, and international recognition. In addition, several technological awards and special recognitions were given for the innovative findings from this project.

The issue of global environmental protection has been discussed throughout the world as a major task, especially since the 1992 environmental summit conference held in Brazil. In November 1999, our study on The Development and Practical Application of High Performance Industrial Furnaces won the highly honorable 9th Nikkei Global Environmental Technology Grand Prize Award. The reason this project was so honored is that its new technological advances and developments have demonstrated the possibility of reducing energy consumption by about 30%, NO_x emission by about 50%, and equipment size by about 25%. These technological achievements established a new landmark, which was difficult to envision by many professionals and colleagues throughout the world. These results were highly appreciated by high government officials in Japan. We have very high expectations from this project. We believe that our technology will not only be utilized in several industries in Japan, but also be gradually transferred to many other countries. We also believe that this innovative technology, originating in Japan, will provide a major contribution to environmental protection on a global scale.

We will make our best efforts to promote and widely spread the high performance industrial furnace technology on a wide scale. We will also make dedicated efforts to expand this technology further for use in other technological areas that utilize fuel as an energy source.

This book is the culmination of this 7-year project. The book also highlights some recent accomplishments made in Japan and abroad on some peripheral and application technologies in cooperation with several universities and research institutions. We are indebted to all those who have contributed in any capacity to the development of this technology. Some of the organizations, industries, universities, and institutions contributing to this technology development effort are cited here.

This book represents the outcome of the collective efforts of many scientists and engineers from the related industry and academia. I would like to take this opportunity to express sincere gratitude to all the participants, including the corporations that undertook subcommissioned assignments, the personnel from academia and industry, and those from the Ministry of Economy, Trade and Industry (METI, formerly MITI) and NEDO. I hope that this book will prove to be of value to worldwide members of the technical community from the industry, academia, research organizations, and government.

Finally, I wish to thank all members of the technical community whose diligent efforts led to the outstanding success of this major undertaking by the Japanese government. Their efforts will be remembered not only in Japan but also worldwide. I wish to acknowledge my predecessor, the late Ryoichi Tanaka, President of Nippon Furnace Kogyo Kaisha Ltd. (NFK), who served as the chairman of JIFMA for all the research and development efforts. He devoted his whole life to the improvements of industrial furnace technologies and struggled to develop high performance industrial furnaces and high temperature air combustion technologies until the end. We owe our gratitude to his lifelong dedicated efforts on evolutionary and revolutionary combustion and heat transfer technology developments.

Tadashi Tanigawa
Chairman, Japan Industrial Furnace
Manufacturers Association

August 2002

Preface

This book is a comprehensive and illustrated work on high temperature air combustion (here called HiTAC), which has revolutionized our paradigm on the use of all kinds of fossil, alternative, waste, and derived fuels for energy conversion and energy utilization in industry. Significant experimental knowledge and insights from many practical devices have resulted in the utilization of HiTAC technology for many applications. The traditional definition of flame is that which gives heat and light during chemical reaction between reactants. However, under certain conditions with some fuels, this definition of flame can be revised.

The text is oriented toward the person who wishes to gain a good understanding of the principles and practice of HiTAC. The text also allows one to apply this technology to achieve significant energy savings, to reduce the size of equipment and environmental pollution, including CO_2, for specific applications. Combustion technology utilizing preheated combustion air in excess of 1000°C has drawn significant worldwide attention for many applications. The basic concept is that the combination of maximum waste heat recovery by high cycle regenerator and controlled mixing of highly preheated combustion air with burned gases yields uniform and relatively low temperature flames. Indeed, the revolutionary HiTAC technology has been demonstrated to provide simultaneous reduction of CO_2 and nitric oxide emissions and to reduce energy consumption for a specific process or requirement. Specifically, HiTAC has been demonstrated to provide about 30% reduction in energy (and hence also CO_2 emission), 50% reduction of pollutants, and about 25% reduction in the physical size of the facility compared with the conventional type of furnace design. Furthermore, extremely low levels of nitric oxide emissions, far below the present regulations, have been demonstrated in several field trials.

This book describes the development of HiTAC technology and its practical application to different kinds of furnaces of importance in industry. Future potential applications of this technology are also presented. Recognition of the vast scope and importance of HiTAC technology has prompted CRC Press to include the present text in their series of books on Environmental and Energy Engineering.

Other texts in the series delve deeply into other specific areas. This book focuses on all aspects and applications of HiTAC; good characterization of the combustion phenomena with high temperature combustion air is of prime concern. Particular reference is made to the work published in this area during the last decade. Other valuable information may be found in various research reports and journals in Japan and from international symposia and journals.

Chapter 1 describes the innovation of HiTAC, as well as the historical background and evolution of this combustion technology. Chapter 2 discusses the combustion phenomena associated with high temperature air combustion. A comprehensive view is provided of the fundamental differences in the thermal, chemical, and fluid dynamic characteristics of the flame. HiTAC technology provides significantly higher flame stability at all fuel–air mixtures (including very lean fuel mixtures), higher heat transfer, and low heat loss from the stack (waste heat). The fundamentals of gas, liquid, and solid fuel flames are also presented from the point of view of HiTAC. Also included here are the significantly different flame features, flame stability, reduced emissions, and significant energy savings with HiTAC. The flame color is found to be much different from the usually observed blue or yellow. Under certain conditions bluish green and green color flame has been observed using typical hydrocarbon fuels. In contrast, flameless (or colorless) oxidation of the fuel has also been observed. These characteristics of flames have not been cited before in the literature. In Chapters 3 and 4 the models for simulating high temperature air combustion as well as the impact of HiTAC on industrial furnace performance are presented. Chapter 5 provides the design guidelines for high performance industrial furnaces. General and optimal design guidelines for various kinds of furnaces, such as reheating furnaces, heat treatment furnaces, and melting furnaces, are presented from the point of view of higher heat transfer, reduced size, reduced pollution, and higher performance. Experience and field trials on different kinds of practical furnaces are also presented. In Chapter 6, potential applications of HiTAC to other energy-using sectors are presented. Some of the examples include the conversion of coals, biomass, and solid waste fuels to cleaner fuels, fuel reforming, stationary gas turbine engines, internal combustion engines, and many other advanced energy-to-power conversion systems. Reference data from several high performance industrial furnaces are also included as an appendix to the book.

This book is the first to be published on high temperature air combustion, including fundamental aspects, its practical use in furnaces and boilers, potential applications in other energy conversion systems, and projected developments and trends. We hope that our readers will be stimulated by the new developments in equipment for energy saving and low pollution for industry and commerce. The authors of any specialized text must select, abstract, and reframe the material that they find most suitable for exemplifying the principles and techniques. In this book we have selected the work of several prominent researchers. Nevertheless, a special attribute of this book is the strong practical emphasis of the portrayal of those concepts, which may be difficult to understand and apply. We have tried to strike the best balance among the physical, practical, and mathematical aspects, and to produce a text that appeals to students and practicing engineers in applying the latest available knowledge to solve their practical energy conservation needs and environmental pollution reduction.

The book is intended as a basis for engineers and researchers in the area of energy conversion using fuels, and also as a textbook for senior year undergraduate and graduate students. The scope of the book is to provide a solid foundation for those who intend to utilize HiTAC technology for their specific application for energy conservation and pollution reduction.

We wish to acknowledge the work of all those who contributed and collaborated on HiTAC research and development activities and of those who assisted in the preparation of this book. We are particularly grateful to our numerous colleagues in Japan and throughout the world who provided us with information for inclusion

here. Specific acknowledgment to authors and sources is made in the text and in the lists of references. Special thanks are due to all the industries, institutions, and organizations listed in the Acknowledgments as well as the authors who have contributed to this book. Their help, support, encouragement, and friendship were most welcome. We wish to acknowledge the late Ryoichi Tanaka, President of NFK, for his vision and leadership on the development of HiTAC technology. All members of the technical community worldwide will remember him for his commitment and devotion to developing advanced furnaces. We are grateful for his lifelong dedicated efforts on the evolutionary and revolutionary burner and furnace technology developments. Finally, we most gratefully wish to thank CRC Press for their special cooperation in careful preparation of the book.

Hiroshi Tsuji
Ashwani K. Gupta
Toshiaki Hasegawa
Masashi Katsuki
Ken Kishimoto
Mitsunobu Morita

August 2002

The Authors

Hiroshi Tsuji was promoted to Professor of Combustion Science at the University of Tokyo in 1962. Since 1984 he is Emeritus Professor of the University of Tokyo. He became a member of the Japan Academy in 1992. He has made an honorable achievement through study on the fundamental aspects of flames, using a porous cylinder burner, called the "Tsuji burner". Professor Tsuji was awarded the Bernard Lewis Gold Medal (the Combustion Institute) in 1988, the JSME Thermal Engineering Achievement Prize in 1990, the Japan Academy Prize in 1990, and the Second Order of the Sacred Treasure in 1993.

Ashwani Gupta is Professor of Mechanical Engineering at the University of Maryland, College Park. He received his Ph.D. in 1973 and D.Sc. in 1986, both from Sheffield University, UK. He has co-authored 2 books, edited 10 books, and published over 300 archival papers. He is a Fellow of AIAA, ASME, and the Institute of Energy, UK. He received the AIAA Energy Systems award in 1990 and Propellants and Combustion award in 1999, and the ASME George Westinghouse Gold Medal award in 1998. He also received several best paper awards from AIAA and ASME. He is an associate editor for *AIAA J. Propulsion and Power* and co-editor of the Environmental and Energy Engineering series of books published by CRC Press.

Toshiaki Hasegawa is Director and General Manager of Combustion Equipment Division at Nippon Furnace Kogyo, Yokohama. He graduated from the Metallurgical Engineering Department at Iwate University and participated in a combustion engineering course at Waseda University in 1977. He joined NFK in 1974 and has been working on the development of technologies for high intensity combustion and low NOx combustion for industrial furnaces and boilers. In 1999, he was awarded the Grand Technology Prize of Ohkouchi Memorial Foundation following R&D on high temperature air combustion heating system. In 2000 he received the Best Paper Award from the Combustion Society of Japan.

Masashi Katsuki is Professor of Osaka University, Department of Mechanophysics, School of Engineering. He was the chairman of the Thermal Engineering Division of the Japan Society of Mechanical Engineers in 2001, and the Vice President of the Combustion Society of Japan from 1999 to 2000. He is a board member of the Japan Society of Mechanical Engineers, the Combustion Society of Japan, and the High Temperature Society of Japan. He was awarded Best Paper Awards from the High Temperature Society of Japan in 1990 and 1995, Gas Turbine Society of Japan in 1996, Japan Society of Mechanical Engineers in 1997, and the Combustion Society of Japan in 2000.

Ken Kishimoto is Professor of Mechanical Engineering, Graduate School of Technology at Kokushikan University. He is a graduate of Waseda University. He obtained his Masters degree from Waseda University in combustion engineering. He is experienced in the fields of combustion dynamics, and heat and energy engineering. He has published a number of papers on electrical augmented combustion, combustion driven oscillation, combustion noise, pulse combustion, and high temperature air combustion.

Mitsunobu Morita is General Manager of Technology and Senior Researcher in High Performance Industrial Furnace Development Center, Japan Industrial Furnace Manufacturers Association. He graduated from the University of Tokyo in Mechanical Engineering in 1967. He obtained his Masters degree from the University of Tokyo in 1969, and Doctorate degree from Nagoya University in 2001. He has worked in the field of thermal engineering and process engineering for 30 years after joining Nippon Steel Corporation in 1969. He is experiencee in the development and applications of surface combustion in sintering furnace, new hot strip mills reheating furnace design and construction, and reduction burner with strong recirculation.

Acknowledgments

The authors sincerely acknowledge the New Energy Development Organization (NEDO), and the Japan Industrial Furnace Manufacturers Association (JIFMA) for supporting this work. One of the authors, A. K. Gupta, would like to acknowledge the support provided to him by the National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and NFK. He would personally like to acknowledge the support and friendship provided by late President Ryoichi Tanaka of NFK and to Dr. R. H. Woodward Wesche for his valuable comments in the entire manuscript. The support and contributions provided by the following individuals from academia, industry, and research are gratefully acknowledged.

Prof. Hiroshi Taniguchi, Hokkai Gakuen University
Prof. Masatake Sadakata, University of Tokyo
Prof. Emeritus Toshisuke Hirano, University of Tokyo
Prof. Masanobu Hasatani, Nagoya University
The late Prof. Kazutomo Ohtake, Toyohashi University of Technology
Dr. Kiyoshi Sugita, Nippon Steel Corporation
Hiroshi Mitsukawa, Tetsuo Ohmura, Toru Yamauchi, Shinichi Nishioka, Yoshio Takagi, New Energy and Industrial Technology Development Organization (NEDO)
Prof. Akira Yoshida, Tokyo Denki University
Prof. Yoshio Yoshizawa, Tokyo Institute of Technology
Prof. Kuniyuki Kitagawa, Nagoya University
Prof. Nilson Kuniyoshi, Okayama Prefectural University
Prof. Ichiro Naruse, Toyohashi University of Technology
Prof. Atsushi Makino, Shizuoka University
Prof. Hideyuki Aoki, Tohoku University
Prof. Roman Weber, Technische Universität Clausthal, Germany
Shinichiro Fukushima, Shunichi Sugiyama, Toshikazu Akiyama, Yutaka Suzukawa, Toshio Ishii, Yoshimichi Hino, Tatsuya Shimada, NKK Corporation
Susumu Mochida, Makoto Miyata, Jun Sudoh, Takeshi Tada, Kiyobumi Kurita, Tadahiro Araake, Nippon Furnace Kogyo Kaisha, Ltd
Jyunichi Hayashi, Dr. Hideki Murakami, Toshiaki Saitou, Masataka Hase, Atsushi Hida, Nippon Steel Corporation
Kouji Murakami, Morihiko Imada, Hisamichi Otani, Masao Uede, Chugai Ro Co., Ltd
Kenjiro Sato, Yoshiyuki Tomita, Daido Steel Co., Ltd
Osamu Takeuchi, Kazumi Mori, Toru Yoshida, Ishikawajima-Harima Heavy Industries Co., Ltd

Katsumi Hazama, Takayuki Inami, Sanken Sangyo Co., Ltd
Hirokiyo Shimomura, Jyunichi Ninomiya, Rozai Kogyo Kaisha, Ltd
Dr. Hideo Tai, Masayuki Tamura, Dr. Ryoichi Toriumi, Tokyo Gas Co., Ltd
Masahiko Nakahara, Yamatake Corporation
Hirotaro Kouhata, Yokogawa Electric Corporation
Eizo Maeda, Kawasaki Refractories Co., Ltd
Yasuo Moriguchi, Cosmo Oil Co., Ltd
Katsuyoshi Kobayashi, Taketo Sasaki, Tsutomu Yasuda, JIFMA

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1 Introduction

1.1 HISTORICAL BACKGROUND OF HIGH TEMPERATURE AIR COMBUSTION

Global energy consumption in recent years has continued to increase not only in developed countries but also in developing countries, primarily as a result of rapid industrialization and improvement in the standard of living. This increased energy consumption has led to increased emissions of carbon dioxide and nitrogen oxide into the environment. Because energy and environmental issues have become of prime concern, it is now a matter of great urgency to deal with environmental preservation on a global scale and over a longer time duration. Under these circumstances, combustion technology utilizing preheated air in excess of 1000°C has drawn increased attention in many application areas. This combustion technology enables one to contribute greatly to the simultaneous reduction of carbon dioxide and oxides of nitrogen emissions. This high temperature air combustion (HiTAC) has achieved approximately 30% reduction in energy (and hence also carbon dioxide emission) and 25% reduction in the physical size of facilities as compared with the traditional type of furnace. Furthermore, HiTAC technology has demonstrated extremely low levels of emissions of nitric oxide, which are far below the present regulatory standards. This book describes the development of this attractive and innovative HiTAC technology and its practical applications to different kinds of furnaces for many industries.

1.1.1 Environment and Energy Conservation

In 1992, the United Nations Conference on the Environment and Development (the so-called Earth Summit) was held in Brazil with the objective of establishing international initiatives for the preservation of the global environment. In December 1997, the Kyoto Protocol was held on Global Climate Changes as the Third Conference of Parties (COP3) to the United Nations Framework Convention. At this conference it was stipulated that developed countries should reduce their total emissions of greenhouse gases by at least 5% from the level of 1990 between the years 2008 and 2012. Therefore, the reduction of carbon dioxide emissions became an urgent issue, particularly from those industries that consume large amounts of fossil fuel.

In many developed countries, including Japan, both energy consumption and industrial activities are quite vigorous. It has become an important responsibility for all developed countries, including Japan, to endeavor to achieve both environmental preservation and industrial growth by developing efficient and environmentally friendly energy utilization technologies, which harmonize with the conservation of resources and energy saving. Against this background, the Ministry of International

Trade and Industry (MITI) in Japan embarked on the *Development of High Performance Industrial Furnaces and the Like Project*. The project, aimed at developing an outstanding energy-saving technology for the 21st century, focused on significant reduction in energy consumption and simultaneous contribution to environmental preservation.

The *Development of High Performance Industrial Furnaces Project* has been implemented since 1993 as one of the activities of New Energy and Industrial Technology Development Organization (NEDO). The objective of this project has been to advocate the establishment of a basic concept for innovative technology. The research and development on the above-mentioned advanced combustion technology have been mainly conducted by the industrial sector during the 7-year history of the project. The fundamental research related to the technology has been carried out by the academic sector through cooperative exchange of information with the industrial sector. This research cooperation between academia and industry has played an important role in promoting the unique research and development of the project.

1.1.2 Reduction of Pollutant Emissions and Energy Crisis

Before the 1960s, the combustion technology had made magnificent progress. But, from the 1960s into the early 1970s, two new serious problems have emerged that result from combustion technologies.

The first was the problem of pollutant emission generated by combustion, such as sulfur oxide (SO_x), nitrogen oxide (NO_x), and smog. The other was the requirement for efficient use of energy caused by the oil crisis.

In developed countries the problem of air pollution has been caused by the combustion exhaust emissions brought by the rapid expansion of industrial production and the remarkable prevalence of motorization in the private sector. It has become a serious social problem. Legal regulations for the restriction of pollutant emissions have been enforced. To cope with this problem, each industry worked intensively on the development of combustion methods and combustion units with low levels of pollutant emission. During the development process of new combustion technology, a particular focus was on low NO_x burners and engines. Intensive research was conducted on the mechanisms controlling the generation and reduction of NO_x. It is also widely acknowledged that the achievements of Japanese industry in the development of new combustion technologies on low NO_x emission have been superb and well recognized by the technical community. This is supported by the many patents taken by industry.

With the oil crisis of 1973, the problem of the energy crisis was suddenly highlighted. Every energy-consuming sector has placed emphasis on the development of a combustion system with low fuel consumption. Furthermore, attention was focused on such issues as the effective combustion of alcohol, various low-grade fuels, etc., which had not been used before as principal fuels. An ultra-lean mixture is defined as a fuel/air lean premixed gas mixture with the fuel concentration near to the lower flammability limit. Because combustion of this ultra-lean mixture had not been possible under usual conditions, a new method to accelerate the reaction by using some type of mechanism has been sought. The evaluations of the combustion of ultra-lean mixtures have varied depending on the positions of the evaluators. However, research on the combustion of ultra-lean mixtures at the combustion limit has been a challenge to combustion engineers and attractive to researchers in the field. Because ultra-lean mixtures do not burn under normal pressure and temperature conditions, it becomes necessary for the mixture to accelerate the reactions by methods such as: (1) catalytic oxidation using a catalyst, (2) injection of active particles such as high energy radicals, (3) preheating, or (4) increase of pressure. Among these, except for oxidation with catalyst, interest has focused on a method of preheating the ultra-lean mixture using a heat recirculation method. The heat recirculation method mentioned here is proposed as a method of preheating the unburned mixture without using external energy. The method provides a means of recirculating the heat from the high temperature side (burned gas) back to the unburned mixture side using an appropriate heat exchange method. The preheating gives additional enthalpy to the unburned mixture without dilution by the combustion products. The combustion system utilizing heat recirculation, in fact, has been commonly used in industrial combustion units for many years. The methods of recovering waste heat and preheating combustion air using various types of heat exchangers have been employed primarily to improve thermal efficiency and stable combustion. Here, it should be pointed out that the high temperature air combustion technology is an extension of the above means. Therefore, from an industrial perspective, the heat recirculation combustion method used for the combustion of ultra-lean mixtures is not, in principle, a totally new method of combustion.

In 1971, Weinberg[1,2] of Imperial College perceived the fact that preheating the mixture using the heat recirculation method can attain stable combustion of an ultra-lean mixture and expand the flammablilty limits of the mixture. He proposed the concept of additional enthalpy combustion for ultra-lean mixtures. A special feature of this method is that a heat source for preheating is not necessary to maintain combustion except at the time of start-up. Furthermore, the temperature of the final exhaust gas does not necessarily become high. The novelty of Weinberg's idea lies in maintaining sustained combustion without any assistance from an external heat source, for example, by applying the heat recirculation method used in conventional industrial furnaces for ultra-lean mixtures. In this case, the success of applying the heat recirculation method depends on (1) whether or not a heat exchange method is appropriate and (2) how much of the heat loss from a combustion unit can be reduced. Although various heat exchange methods have been proposed, the major heat recirculation methods studied to date can be broadly classified into (1) indirect (external) heat recirculation methods and (2) direct (internal) heat recirculation methods.

The indirect (external) heat recirculation methods are methods of circulating heat at the exterior of a flame zone without essentially changing the structure of the flame as represented by the double spiral type burner proposed by Lloyd and Weinberg,[1,2] namely, a so-called Swiss Roll burner. The indirect (external) heat recirculation methods can further be classified into methods that mainly utilize conduction only and methods that also actively utilize radiation for the heat feedback. For the latter methods, a combustor was proposed wherein a porous solid wall is positioned to enclose the combustion chamber, because the porous solid wall has the function of converting the sensible heat of gas into radiation energy at a high rate of conversion efficiency. When burned gases behind the flame pass through the porous solid wall, the sensible heat is converted into radiation energy and the unburned mixture is preheated using this radiation energy.

In contrast, the direct (internal) heat recirculation methods are methods of feeding back heat directly from the side of burned gases to the side of unburned gases by inserting, for example, a porous metal with high thermal conductivity into the flame zone, changing the internal structure of the flame and forming an additional enthalpy flame. Many research activities using several of the above-mentioned methods have been conducted in the past and some remarkable research results have been reported.

1.1.3 Panorama of High Temperature Air Combustion Technology

A recuperator was used in large-scale industrial furnaces as a waste heat recovery unit to realize high thermal efficiency and energy conservation. The recovered waste heat was used to preheat the combustion air, which was then fed to a burner. The preheated air resulted in energy conservation and good combustion performance. However, the disadvantages included incorporating a large-scale heat recovery system for waste heat. Furthermore, the temperature of the preheated air was only about 600 to 700°C, at best. To obtain further substantial energy savings, it was found necessary to recover combustion waste heat thoroughly and feed it back to the unburned side effectively. An effective means for achieving this is the development of a regenerative burner having better function for effective waste heat recovery. This has been the topic of active research and development since the beginning of the 1980s.

At British Gas and later at Hotwork International (United Kingdom), throughout the 1970s and the 1980s, substantial efforts were allocated to the development of both recuperative and regenerative burners.[3] Recuperative burners could offer only modest fuel savings, since the combustion air could be preheated to temperatures typically not higher than 600°C. The burners equipped with regenerators (beds packed with ceramic balls) offered much higher preheating levels typically up to a 1000°C with a cycle time of 30 to 40 s. Such substantial air preheating was possible only when the furnace exit gases, entering the regenerator, were at temperatures typically of 1300 to 1400°C.

Further progress in the regenerator design was made in Japan, at Nippon Furnace (NFK), at the beginning of 1990s. New honeycomb-type regenerators were shown to be more compact and possessed smaller thermal inertia. The honeycomb regenerators operated at a very small temperature difference (typically of 50 to 100°C) between the furnace exit temperature and the combustion air temperature. They provided possibilities for achieving combustion air preheating up to 1200°C, thus further improving furnace efficiency.

The technology carried through in the *Development of High Performance Industrial Furnace Project* is high-cycle alternating regenerative combustion technology. It employs high temperature air, preheated to temperatures in excess of 1000°C, using a heat-storage-type heat exchanger that also has short switching time. It has been proved, through extensive research and development efforts to date, that not only carbon dioxide but also nitrogen oxide can be substantially reduced. This type of technology, utilizing high temperature air, has attracted significant attention for the past several decades. For example, since the 1960s, fundamental research has been implemented in the field of special combustion systems, such as a supersonic combustion ram-jet engine, called SCRAM-jet. SCRAM-jet is now attracting attention in the aerospace field, and substantial results have been obtained. However, the technological concept intending to apply high temperature air combustion to conventional industrial furnaces is innovative, and one can say that it is a novel combustion technology because it can contribute to further reduction in energy consumption and promote environmental preservation.

In general, by implementing regenerative combustion, the heat generated by combustion is not uselessly discharged but can be effectively recovered. Therefore, remarkable energy savings (about 30%) and prevention of global warming have been realized. In contrast, it is known that NO_x emission increases with an increase in temperature of the air used for combustion; this has even been shown with numerical simulation on a flame formed in the field of a simple flow. This fact has also been experimentally confirmed in conventional combustion systems, and is now widely acknowledged among researchers and engineers in the field of combustion technology. From the point of view of reducing the emission of pollutants (especially NO_x), many researchers and engineers had doubts on the possibility of utilizing high temperature air combustion. They believed that the technology has not been developed in either the industrial sector or the academic sector. Thus, in the industrial sector, finding a way to achieve a balance between energy savings and reducing emission of a pollutant has been a challenge for many years.

In the meantime, entering the 1990s, unexpectedly reduced values of NO_x were measured in an experimental furnace when high-cycle alternating regenerative combustion technology was applied. The NO_x values were reduced further when the velocity of the airflow injected into the furnace was increased. A concentration of very low NO_x, at most 80 ppm, was confirmed experimentally when the air of a temperature of 1350°C was injected with the velocity of 90 m/s. In addition, because of the temperature rise of combustion air, combustion in a low oxygen concentration atmosphere became possible. The flame was transparent and colorless. This colorless and transparent flame had not been observed previously. In contrast, most flames exhibit a local high temperature as seen in all existing industrial furnaces. Also observed was the fact that combustion proceeds across a wide region in the furnace. The temperature in the furnace is close to the limit of its operation, and the temperature distribution in the furnace is almost uniform. These characteristics revealed that an almost ideal heating furnace can be constructed. Thus, this high temperature air combustion technology has suddenly become the focus of a great deal of attention as a novel combustion technology not only in the industrial sector but also in the academic sector.

The development of this high temperature air combustion technology, especially the development of low NO_x burner technology for natural gas combustion, has been conducted with leadership from the industrial sector. At the beginning of the 1990s, the work at Tokyo Gas led to the development of an advanced fuel direct injection (FDI) concept.[4] The concept utilizes the idea of discrete injection of fuel gas into hot combustion products. During the same time at NFK a lot of efforts were made to reduce NO_x emission using the process of additional enthalpy.[5] The company tested several configurations and designs for air and fuel gas ports. The best results, corresponding to low NO_x emissions, were achieved when the injection ports for fuel and air were positioned apart.

Developments in other countries traveled different routes. Rather than developing new combustion processes, the work focused on burner designs. The flameless oxidation (FLOX) burner, developed in Germany in 1991 to 1992, utilizes a number of air jets, which entrain combustion products before mixing with the fuel.[6] In 1991, the IFRF designed a series of natural gas burners in SCALING 400 studies.[7] Substantial NO_x reduction was achieved when either 80 or 100% of the fuel gas was provided through the individual injectors located on the burner circumference. Furthermore, in this case, NO_x emissions were no longer dependent on preheating of the combustion air. When the burner was fired with 80 or 100% fuel staging, the combustion mode resembled the FDI system. During the tests, it was observed that the radiation heat flux of the staged flame were approximately 20% higher than those of the baseline (unstaged) flame. This, at first, appeared as a surprising result. However, it was later confirmed in other experiments in which, despite the lower flame temperatures with the staged flames, the higher flame volume caused an increase of the heat flux. The most recent developments include a Canadian Gas Research Institute (CGRI)[8] burner that also features discrete injections of fuel gas and air.

Based on the observations of combustion regime in high performance industrial furnaces, which will be shown in later chapters, it could be concluded that the key for high temperature air combustion technology (HiTAC) is the dilution of fuel and combustion air by burned gases in the furnace. Specifically, combustion in an atmosphere of low oxygen concentration is the key. This situation can be realized by the recirculation flow induced by high velocity air injection. These clarifications in terms of the true HiTAC mechanism have provided a framework within which the technology could be utilized for specific applications for energy conservation and pollution reduction.

1.2 INNOVATION OF HIGH TEMPERATURE AIR COMBUSTION

1.2.1 FUNDAMENTALS OF COMBUSTION

1.2.1.1 Heat Recirculating Combustion

Preheating of combustible mixture by recycled heat from flue gases has been considered an effective technology not only for combustion of low calorific fuels but also for fuel conservation. It is called heat-recirculating combustion in which reactants are heated prior to the flame zone by heat transfer from burned products without mixing of the two streams.[9] The temperature histories of premixed combustion in a one-dimensional adiabatic system are schematically compared in Figure 1.1[1,2] for

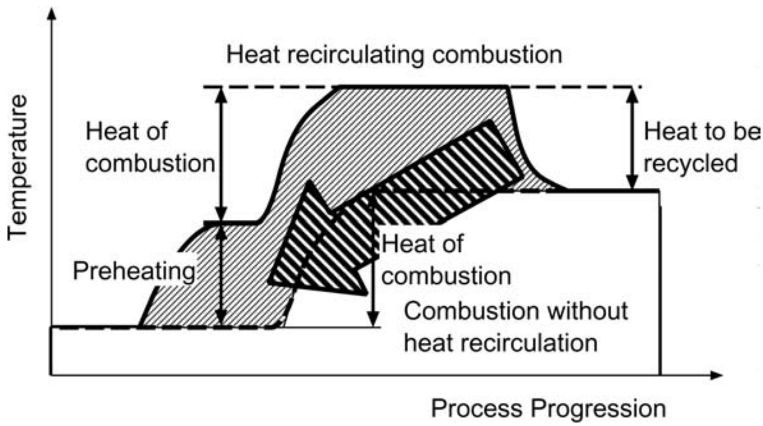

FIGURE 1.1 Temperature history of heat-recirculating combustion of premixed reactants in one-dimensional adiabatic system.

the cases with and without heat recirculation. The maximum temperature in heat-recirculating combustion is determined by the amount of recycled heat that is independent of the equivalent ratio of the mixture or the calorific value of the fuel used. This is certainly true for premixed combustion in adiabatic condition. Accordingly, it has been held that heat-recirculating combustion brings a temperature rise throughout combustion processes in proportion to the amount of recycled heat.

At normal ambient temperature, an ordinary hydrocarbon gaseous fuel mixed with atmospheric air exhibits a combustible domain around the stoichiometry, and an increase of temperature of the mixture expands the combustible limits significantly, as illustrated in Figure 1.2.[10] A large increase in the temperature may cause

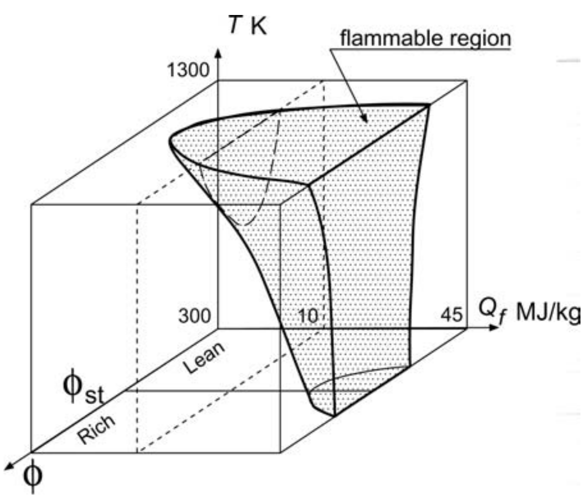

FIGURE 1.2 Flammable domain expressed by calorific value of fuel, Q_f, initial temperature of mixture, T_i, and mixture equivalence ratio, ϕ.

auto-ignition. In contrast, if a fuel of low calorific value is adopted, the combustible domain disappears at ambient temperature and reappears when the mixture is preheated over a certain temperature level, as shown in the figure exhibiting conceptual trends.

Most of the previous research in this field has been aimed at burning ultra-lean mixtures or low calorific value fuels produced in chemical processes or vented from coal mines. In those cases the resultant maximum flame temperature with heat recirculation was not crucial to the tolerance of materials used in the system because of the low calorific value. Further, scientific studies on heat recirculating combustion have been mostly carried out on relatively small-scale premixed flames. However, for large-scale industrial use, diffusion or non-premixed combustion is more common because of its controllability and safety. Heat recirculating combustion in diffusion or non-premixed combustion can be achieved by heating combustion air with the recycled heat from burned products. The temperature of combustion air in an adiabatic system can theoretically be raised to almost the same temperature as the exhaust stream by regenerative heat exchangers. In practice, the regenerative combustion system for implementing high temperature air combustion is the system shown in Figure 1.3, where a heat recirculating method (by use of honeycomb-type regenerators) is applied to a heating furnace. A pair of burners, operating alternately, is used as a unit and the flow path for air ejection in each burner is filled with ceramic

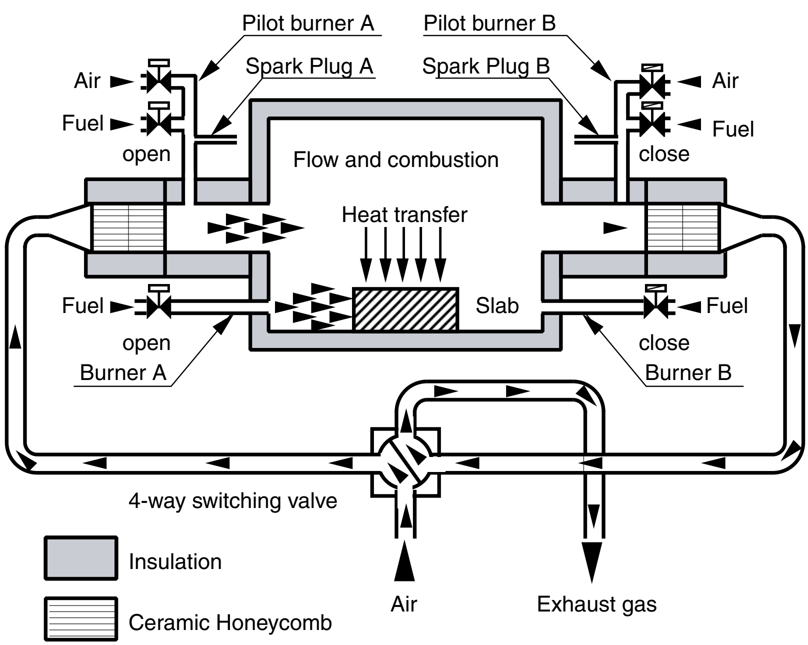

FIGURE 1.3 Schematic diagram of HiTAC furnace operated with high frequency alternating flow regenerators.

honeycombs. Each flow path also acts as a flow path for discharging high temperature burned gases. The high temperature burned gases generated by the one burner are introduced into the flow path of the other side, and the sensible heat of the burned gas is stored in the ceramic honeycomb for a while. Then, the operation of the burner is switched to the other burner, and combustion air is introduced through the ceramic honeycomb by reversing the flow direction. Preheated air at a temperature of about 1273 K is easily obtained and used for combustion. The high-cycle operation, typically 30 to 60 s, is adopted to reduce the heat loss escaping with the waste gas.

The principal merit of heat-recirculating combustion is fuel saving, which is achieved by efficient recovery of waste heat in exhaust gases. Higher preheating temperature assures less rejection of heat with the exhaust, which results in more fuel saving. Therefore, heat-recirculating combustion is surely an attractive technology for future design of any industrial furnaces as far as energy conservation and pollution reduction are concerned. However, it was believed that diffusion flames inevitably harbor near-stoichiometric flame temperature somewhere within their structure, borrowing the words of Weinberg,[9] which tends to generate increased levels of nitric oxides even in great excess air ratio. If stricter air quality regulations, particularly regarding nitric oxides, are applied to furnaces, reduction of nitric oxides in non-premixed combustion is the first issue to be solved for the future utilization of heat-recirculating combustion in a variety of furnaces.

Regarding emissions from combustion systems, it has been generally held that the emission of nitric oxides increases with the temperature rise of combustion air when preheated air is used. Therefore, any practical trade-off between thermal efficiency and emission control has always been a critical issue for designers and engineers. Numerous efforts to strike a balance of furnace between fuel saving and reduction of nitric oxides emission have been made during the last decade. In practice, direct injection of fuel into a furnace,[4,11] high momentum ejection of staging air,[12,13] and mixing control were found to be effective to some extent in reducing nitric oxide emissions in regenerative combustion. Therefore, the practical extent of heat recirculation in industrial furnaces has been specified taking account of the trade-off between energy conservation and tolerance of materials or air quality regulations.

In the process of developing a high-cycle regenerative furnace, extremely low nitric oxide emission was reported from an experimental furnace operated with high temperature combustion air of 1400 K.[5] Because it was difficult to interpret the results, based on existing knowledge of nitric oxide formation mechanisms, this motivated an extensive, collaborative study of high temperature air combustion between industry and academia. Eventually, practical developments and applications of the concept in industry have achieved great progress in energy saving as well as reduction of nitric oxide emission. The details of the technology are explained throughout this book. The basic concept is the combination of maximum waste heat recovery by high-cycle regenerator and controlled mixing of highly preheated combustion air with burned gases to yield relatively low temperature flames.

1.2.1.2 Definition of High Temperature Air

The term high temperature air is used throughout this book. The temperature of the air indicated often varies depending on the situation where it is used. What is the definition of high temperature air when furnace combustion is considered? Imagine that a gaseous fuel at ambient temperature is injected into an air stream. When the fuel mixes with combustion air, some heat is necessary to initiate combustion, and a recirculating flow of combustion products behind a flame holder or a pilot flame is frequently utilized for stabilizing flames in furnaces. However, if combustion air is sufficiently heated prior to mixing, combustion takes place somewhere downstream in the furnace following the mixing of two reactants, even if the flame in the near field of the fuel jet is blown off by a strong shear motion.

Although the temperature level of preheated air does not seem important when discussing preheated air combustion, the fact described above is significant in realizing advanced low NO_x combustion technology, which will be explained later. Therefore, the auto-ignition temperature of a gaseous fuel with air as the limit of high temperature, that is, the air temperature at which a gaseous fuel is ignited automatically in it and in which continuous combustion is sustained, should be called high. Although the definition of high temperature is not given by a fixed value, it is now possible to give high temperature air combustion (HiTAC) a clear meaning. Following the above definition, preheated air combustion (PAC) is defined as combustion with the air of preheated temperature below the auto-ignition limit that has long been utilized in industry.

Once the combustion air is preheated to higher than the PAC limit, a method to stabilize a flame is not necessary for furnace combustion. This auto-ignition temperature of a gaseous fuel varies depending on the kind of fuel and concentration of oxygen of the diluted air. Figure 1.4 shows auto-ignition and combustible limits for propane in preheated air or diluted air with inert gas. auto-ignition and combustion occur even in an atmosphere of oxygen content as low as 3% when it is preheated above 1200 K.

1.2.1.3 Heat Recirculation and Exhaust Gas Recirculation

Global excess air ratio or equivalent ratio is one of the combustion parameters that characterize the operating condition of furnaces. The temperature of combustion products in adiabatic circumstances can be easily defined by the ratio. However, heat subtraction by the material being heated in the furnace and the heat loss from practical systems are influencing factors in defining gas temperature in the furnace. Therefore, the reduced temperature level of burned gas as well as its recycling flow rate largely affects flame temperature with gas recirculation.

Exhaust gas recycling, whether it is internal or external, is an effective method to reduce flame temperatures, and thereby nitric oxides emission. Combustion with normal ambient air usually becomes unstable when the exhaust gas recycling rate, defined as the mass ratio between exhaust gas and fresh reactants, exceeds 30%. As is shown in Figure 1.4, however, a stable combustion domain appears for high rates of exhaust gas recycling, if combustion air is preheated over the auto-ignition

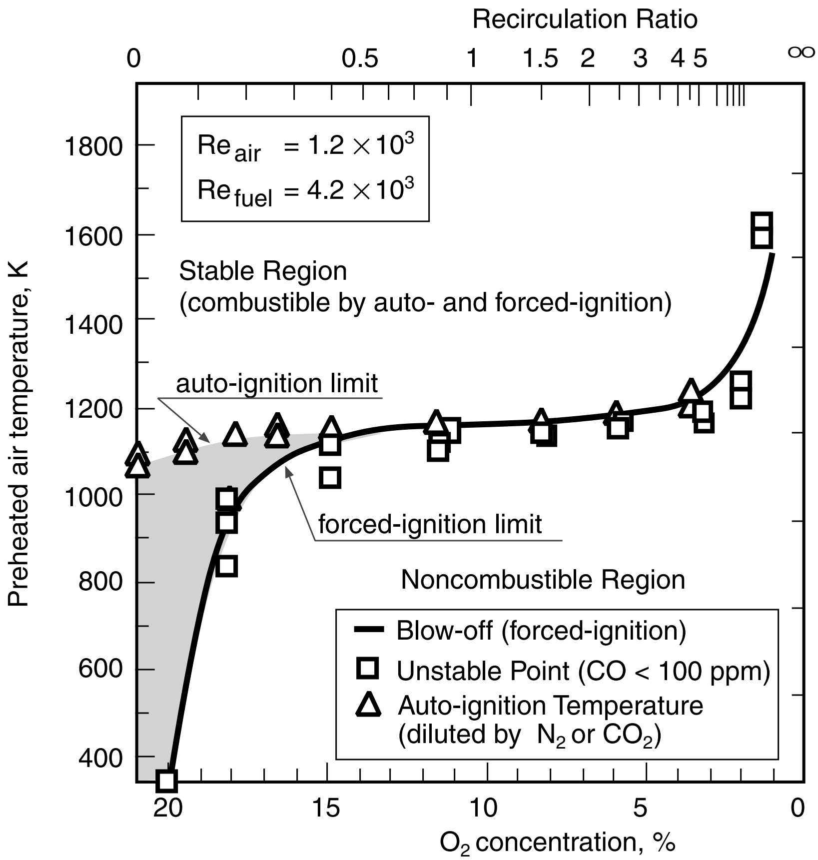

FIGURE 1.4 auto-ignition limits and blow-off limits of propane in a preheated air or a diluted air with nitrogen.

temperature of the fuel. Actually, very diluted air, whose oxygen concentration is as low as 3%, can sustain combustion when it is preheated up to 1200 K.

Hasegawa et al.[14] discussed the individual and multiple influences of heat and gas recycling. In Chapter 2, Figure 2.29 shows contours of the maximum flame temperature on the combined effect of preheated air temperature and recycling rate of burned gases, where *R* is the gas recycling rate. A combination of highly preheated air and high recycling rate of burned product generates relatively low maximum flame temperature. One can understand that the stoichiometric flame temperature in very diluted air, where mass fraction of oxygen is far below the value in normal atmospheric air, is not as high as is usually expected. This is the key for HiTAC when it is applied to practical combustion systems. Keeping the global equivalence ratio constant, the flame temperature in the furnace can be varied or regulated by combining the preheated air temperature and the recycling rate of burned gases.

The concept of the HiTAC is illustrated in Figure 1.5, compared with that of a conventional furnace combustion. Extremely high temperature flames are usually

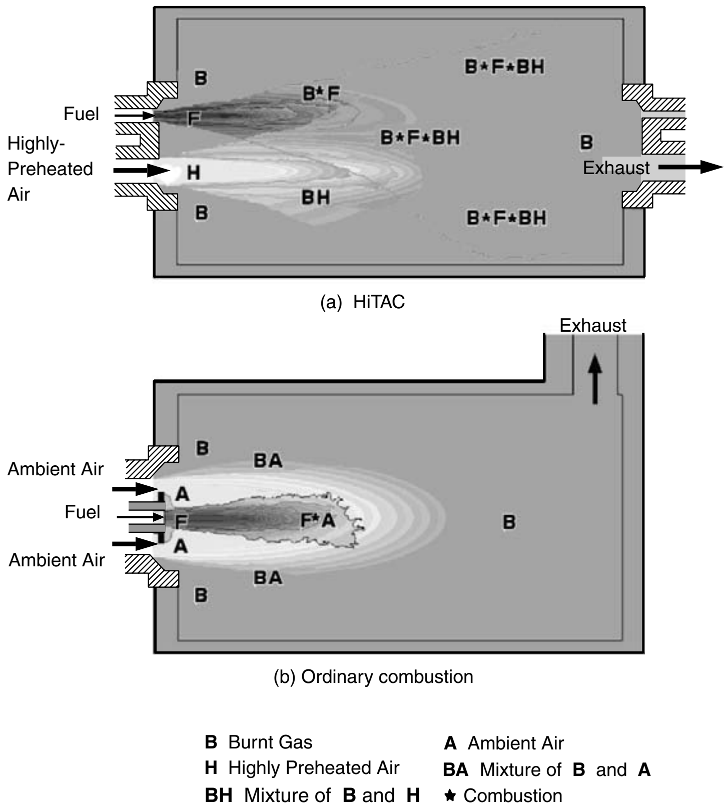

FIGURE 1.5 Mixing and combustion in furnace.

generated in furnaces, if direct combustion between fuel and high temperature fresh air occurs. As a result of the modified furnace geometry, not only extinction of base flames occurs by the shear motion of high velocity inlet air but also the dilution of air with burned gas (BH) must occur prior to combustion by separating fuel and air inlets. Note that those are the conditions in which ordinary combustion cannot be sustained with ambient temperature air. In addition, the fuel injected separately into the furnace also entrains burned gas in the furnace, and some changes in the fuel, such as pyrolysis, decomposition, and vaporization of liquid fuel, if any, during this preparation period. Weak combustion reactions may occur between fuel and entrained product (B*F) and the main combustion follows in the mixing zone of fuel and diluted air with a large amount of burned gas (B*F*BH). The change of flame due to a low concentration of oxygen caused by the high rate of recycling of burned gas probably yields a broadened reaction zone, where relatively slow reactions may be taking place. In established combustion without preheated air, direct combustion between fuel and fresh air (F*A) occurs in the near-field of the burner. Thereafter, some combustion in diluted condition with burned gases may follow in the downstream portion of the flame because of the entrainment of recirculated burned gas by the incoming combustion air. Combustion (F*A) in the vicinity of the burner shows the maximum temperature in the furnace, and most of the nitric oxides emitted from the furnace are formed there. However, combustion in this region is essential to sustain the combustion in the furnace, and whole flame cannot exist if extinction occurs in this portion.

Figure 1.6a shows conceptual temperature histories along streamlines passing through and by the flame zone. The former experiences near-stoichiometric flame temperature, which is slightly below the theoretical adiabatic temperature, T_{ad}, and the latter rises only as mixing progresses. Turbulent mixing between the two produces large temperature fluctuations that can usually be observed in ordinary turbulent flames. If combustion air is preheated, it forces up all temperature profiles to some extent, with the same degree of fluctuations exceeding the theoretical adiabatic temperature of ordinary combustion T_{ad}, as shown in Figure 1.6b. This is a well-known feature of the preheated air combustion (PAC) achieved by use of a recuperator. However, once the preheating temperature exceeds the auto-ignition temperature of the fuel, HiTAC becomes possible. Then, as shown in Figure 1.6c, the temperature history along the streamline passing through the reaction zone shows a relatively mild temperature rise due to slow heat release in a low oxygen concentration atmosphere compared with those in previous cases. The other extreme indicates a temperature profile along the streamline outside the reaction zone, and it rises only with the progress of mixing between preheated combustion air and burned gas recirculating in the furnace. Accordingly, temperature fluctuations generated between these two are very small compared with the previous cases. In spite of the use of highly preheated air, the mean temperature as well as the instantaneous peak temperature is considerably lower in HiTAC than in ordinary combustion.

1.2.2 Principle of Combustion Control for CO_2 and NO_x Reduction

1.2.2.1 Carbon Dioxide

As long as hydrocarbon fuels are used, CO_2 will be emitted in proportion to the carbon content of the fuel, unless it is artificially fixed or removed. The only way for combustion engineers to suppress CO_2 emission from combustion devices is energy conservation by raising the thermal efficiency of the device. In that sense, HiTAC is one of the most attractive technologies for use in the furnace industry. The basic concept is easy to understand. If all of the heat loss and waste from a heating furnace can be eliminated, for example, all the heat generated from fuel will be transferred to the material being heated in the furnace. Therefore, the high efficiency of waste heat recovery is one of the most promising measures available to suppress CO_2 emission, that is, to reduce greenhouse gases. The higher the efficiency of the regenerator, the less CO_2 emitted.

Although available heat in exhaust gases can be transferred efficiently to the incoming cold combustion air using an infinitely long heat exchanger, the actual heat transfer rate is limited by the geometry of heat exchangers. Accordingly, the maximum obtainable temperature of combustion air depends not only on the tolerance of materials used, such as heat-resistance alloys and refractory, but also on heat losses of the system.

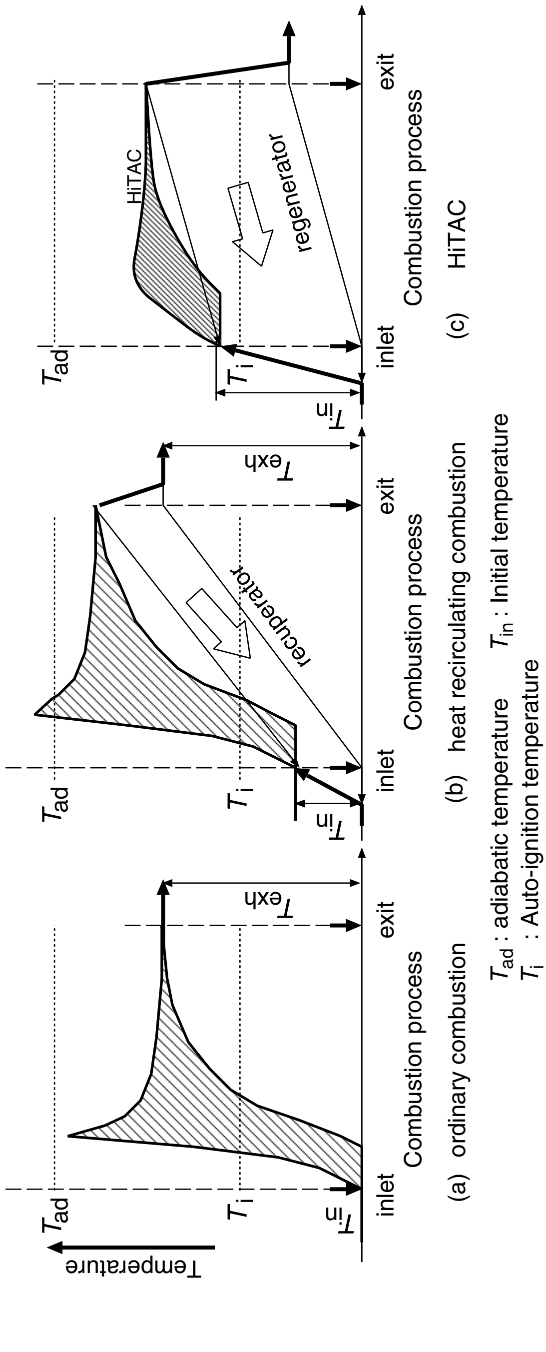

FIGURE 1.6 Conceptual temperature histories and fluctuation intensity.

Regenerators for heat-recirculating combustion appeared first in Europe and studies on heat-recirculating combustion were reviewed by Weinberg.[9] The typical regenerative heat exchanger for preheating combustion air was a bed packed with ceramic balls.

The size varies depending on the cycle time between 30 s to several minutes, which determines the amount of heat storage. A typical regenerator at that time produced preheated air exceeding 1273 K, generally within 300 K below the furnace temperature.[15] However, if the hot gas flow escaping through a shortcut of minimum pressure drop occurs in the bed, it gives rise to uneven temperature distribution in a cross section, resulting in inefficiency of the regenerator.

In contrast, the volume of a honeycomb-type regenerator of necessary heat capacity can be minimized because of its large surface area-to-volume ratio. As a result, direct installation of a regenerator into a burner becomes possible, forming a thermal dam at the exit of the furnace as illustrated in Figure 1.3. Temperature distribution in a ceramic honeycomb is quasi one-dimensional, because ceramic honeycombs assure the uniformity of temperature in a cross section. There is an example in which combustion air of 1570 K was actually obtained by this type of regenerative system for the mean furnace gas temperature of 1623 K, that is, an approximately 50 K difference. Almost constant temperature of combustion air, less than 50 K variation during a cycle, was realized by the use of regenerators with small heat capacity, and about 40% fuel saving, and hence CO_2 reduction, was achieved.[16]

1.2.2.2 Nitric Oxides

During the last quarter of a century, extensive experiments and detailed chemical kinetic calculations have been carried out to clarify the formation mechanisms of nitric oxides. As a result, the temperature rise in combustion air has been recognized as one of the influencing factors on nitric oxides emission from combustion systems because it often causes higher flame temperatures, where most nitric oxides are rapidly formed. The influence of inlet air temperature on nitric oxides emission from a prototype furnace is shown in Figure 1.7, demonstrating an exponential increase of nitric oxide emission with temperature rise of combustion air. These characteristics have been widely taken among combustion engineers as common knowledge of nitric oxides emission from combustion devices.

Clearly a large amount of nitric oxide is formed with the increase in flame temperature. Consider what will happen when preheated air higher than the auto-ignition temperature of a fuel is used. If reaction between fuel and preheated normal air at near-stoichiometric ratio occurs, the flame temperature must be extremely high. Therefore, a large quantity of nitric oxides may be emitted when non-premixed combustion takes place with high temperature pure air in furnaces. If this happens, the reduction of nitric oxides in HiTAC seems unpromising. There is one more important dependency factor that needs to be discussed. This is the oxygen concentration in the reaction zone where local combustion reactions take place. Combustion always occurs in near-stoichiometric mixture even though the mixture is non-premixed. However, when referring to stoichiometric ratio, few

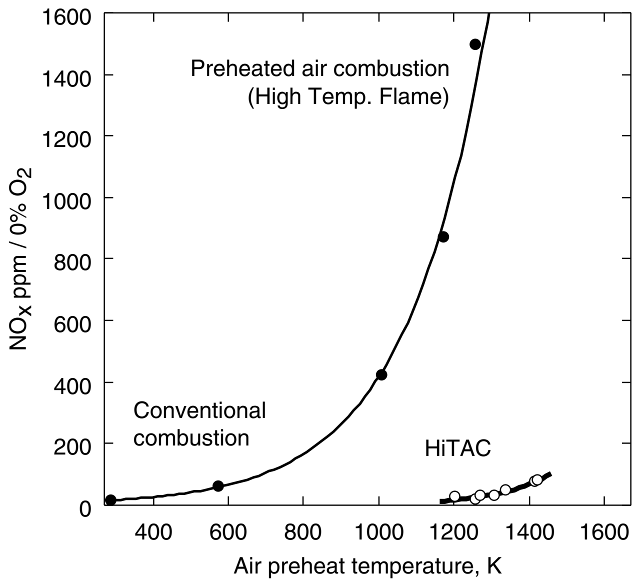

FIGURE 1.7 Preheated air temperature on NO_x emission.

people refer to the actual concentration of oxygen because utilization of atmospheric air as the oxidizer in practical combustion systems is far too common to be noted. Thus, we must pay special attention to the influence of oxygen concentration on nitric oxide formation.

Suppose that we use highly diluted air with inert gas such as nitrogen for combustion. Figure 1.8 shows numerically predicted turbulent diffusion flames between methane and air or their dilution together with their temperature and species concentration profiles across the flame. The ordinary methane–air flame has a typical thin reaction zone called a flamelet, where rapid combustion reactions produce a steep concentration gradient in methane and oxygen as well as a sharp and high-temperature rise due to the heat release in the flamelet. In contrast, the diffusion flame between diluted methane (40%) in nitrogen and diluted air in nitrogen, in which actual oxygen concentration is 8%, shows a broadened reaction zone associated with a lower peak temperature in spite of the preheating of both flows up to 1273 K. The unexpected low flame temperature is caused by a combination of high preheating of reactants and the dilution by a large amount of inert gas. Because the local reaction rate becomes small in diluted circumstances, increased volume of the reaction zone results from burning fuel at the same rate as ordinary combustion, hence the same total heat release rate in the furnace. Therefore, the reaction and heat release zone of combustion in the dilution with plenty of burned gases may become widely distributed compared with that of ordinary combustion and yield a mild temperature rise locally. These facts must be taken into account when attempting to suppress nitric oxides emission from practical HiTAC systems.

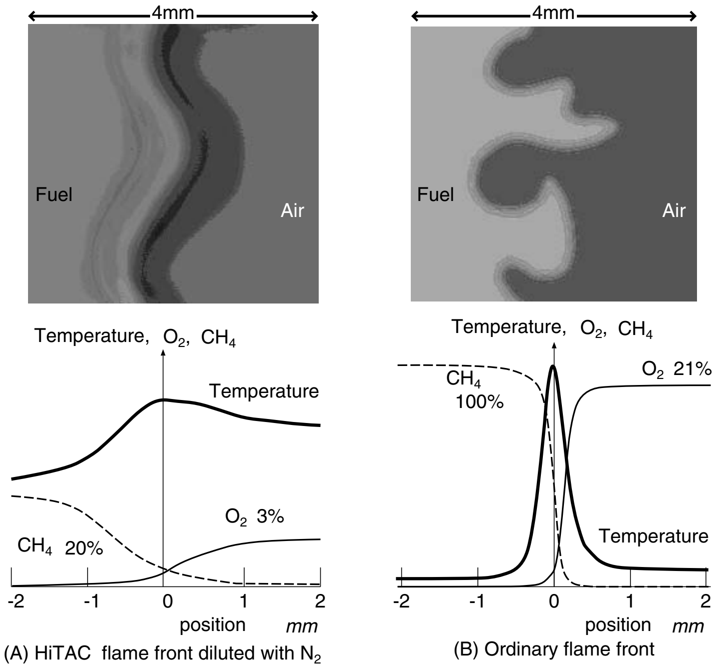

FIGURE 1.8 Thickness of reaction zone and temperature rise.

1.2.3 Heat Transfer in High Temperature Air Combustion

Heat transfer in furnaces depends not only on the internal temperature distribution but also on the physical properties of combustion gases and of furnace walls. Although the heat transfer rate is augmented with the increase of furnace temperature, there is a maximum operating temperature due to the maximum temperature limit of furnace materials used, such as fire bricks. Also, temperature fluctuations in turbulent combustion, because a peak temperature at an instant, sometimes deteriorates the surface of the material being heated or the insulation on the wall. Therefore, we must achieve effective heat transfer under these limitations.

An earlier section explained that temperature fluctuations in HiTAC are much smaller than in ordinary combustion. This fact allows us to raise the operating temperature because a small instantaneous peak temperature does not exceed the limit. So, it is possible to increase the combustion load for the same size furnace. Or, we can reduce the furnace size by adopting HiTAC for the same combustion rate.

If combustion air can be preheated to a high temperature at the entry of a furnace using the recovered sensible heat, it can save some quantity of energy in heating the materials to the specified temperature. The heat capacity of the material being heated does not change because of the operating systems or because of the heat input to the furnace. However, the efficiency of heating, the heating time, and the uniformity of temperature rise of the material being heated do change depending on the local heat release rate in the furnace as well as on the resultant temperature distribution. We consider the heat transfer in furnaces from this point of view.

To realize the effective heat transfer in HiTAC furnaces, discussion is required on each mode of heat transfer (conduction, convection, and radiation). Among these, conduction from flames to the materials being heated is not so important when we consider the heat transfer in furnaces, although conduction is important when we discuss the depth of heating in the material. Thus, it is enough if conduction is taken into consideration only when the loss through furnace walls is discussed.

1.2.3.1 Convection Heat Transfer of High Temperature Air Combustion

The heat transfer in a conventional industrial furnace can be described in the schematic diagram shown in Figure 1.9. The convection heat transfer comprises a very small proportion of the total heat transfer rate from combustion gas to the material being heated. The heat convection rate is expressed by the product of heat transfer coefficient, contact area, and the temperature difference between the solid surface and its adjacent gas. The characteristic length of convection heat transfer depends on the boundary layer thickness. If there is a large deviation in the spatial distribution of temperature in combustion gases, the local convection heat transfer will generate nonuniform heat flux onto the material, and hence the temperature distribution on the surface. The redistribution of heat will follow by way of radiation and conduction, which will take somewhat longer.

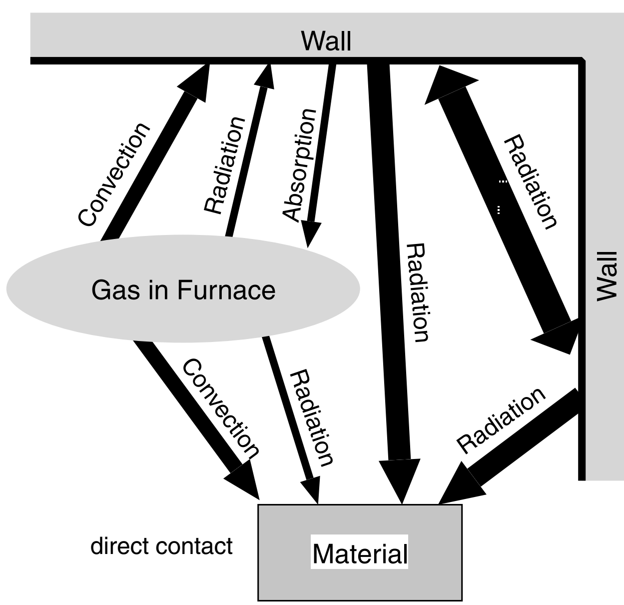

FIGURE 1.9 Heat transfer in furnaces.

We may consider that a similar mechanism as shown in Figure 1.9 is still valid in HiTAC furnaces. However, from the viewpoint of the material being heated and the furnace walls, it is not necessary to consider the heat conduction in a solid due to the uniform heating resulting from the small deviation in temperature distribution. That is a characteristic feature of heating in HiTAC furnaces. Furthermore, as is described in a later section, the characteristic length of radiation heat transfer is large and the energy, which travels as an electromagnetic wave, can be transferred from frontside to backside of a furnace directly. Therefore, because wide wall surfaces are usually maintained at a nearly uniform temperature in HiTAC, heating by radiation dominates the heat transfer in the furnace. The direct convection heat transfer to the material being heated plays only a supplementary role.

Nevertheless, convection heat transfer in HiTAC is important as an initiator of heat transfer in the furnace. Since flames in HiTAC are not like conventional luminous flames but are blurred with low luminosity, as shown on the cover photograph of this book, we cannot expect effective radiation heat transfer from flames to materials being heated. However, the convection heat transfer from gas to walls works as the starting point for heat transfer in the furnace.

A simulation dealing with reaction and heat transfer in three dimensions is described in Section 3.4 in this book; we show another example here. This simulation was carried out assuming that the flame temperature was constant, and each element in the furnace, such as a wall surface, flame zone, and material being heated, was treated as a distributed constant. The dependence of radiation heat transfer on wavelength was considered. The flame gas absorptivity was expressed using the band absorption of CO_2 and H_2O by taking the respective mole fractions into account. Wall surface was regarded as a selective absorption surface, assuming typical refractory. As a result, it acted as a low absorption body for far-infrared radiation having a wavelength longer than 4 μm, and as a blackbody for a wavelength shorter than 2 μm. The furnace was a small rectangular furnace (length 2.5 $\times$ width 1.2 $\times$ height 0.8 m, Al_2O_3 wall thickness 0.3 m), in which a flame was positioned in the center and oriented longitudinally and the material being heated was placed 0.3 m above the bottom surface.

Some of the results are shown in Figure 1.10. As the emissivity and absorptivity of flame become smaller, the ratio of the radiation heat transfer from flame to wall to the convection heat transfer to the wall becomes smaller. On the contrary, the contribution of radiation heat transfer in the total heat transfer to the material being heated increases. This is in contrast to our expectation when the flame is in low luminosity. This is a result of the increase of radiation heat transfer from walls, which are heated by the convection, to the materials being heated. Therefore, the thermal field in a furnace is retained in equilibrium by radiation heat transfer. This has a long characteristic transfer distance, when the flame luminosity is low. It means that the field is dominated by radiant heat, and the necessary heating time is shortened by the change of luminous flames into nonluminous ones.

The increase of radiant heat transfer between walls means the rapid redistribution of the heat, transferred by local convection, to other walls. Therefore, the radiant heat from a wall covers most of the heat flux to the material being heated, although

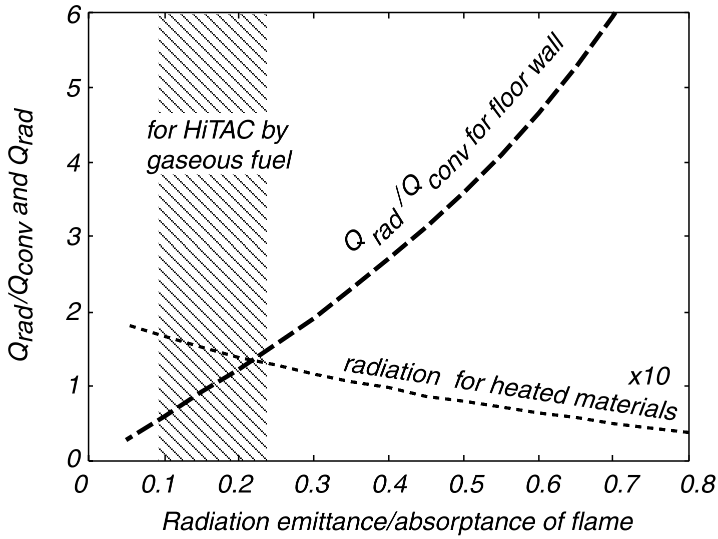

FIGURE 1.10 Radiation and convection heat transfer in furnaces.

the direct radiation heat transfer from flame to the material being heated is small compared with the heat transfer in a conventional combustion furnace. The increase from the effect described above can be considered as the effective increase in the exchange area, or configuration coefficient, of radiation heat transfer.

As explained above, in HiTAC where a flame is nonluminous, the convection heat transfer to the wall triggers the radiation heat transfer to the material being heated. The precise convection heat transfer coefficient depends mainly on the orientation and velocity of the flow. At the same time, it is more effective to agitate the flow and to avoid the development of a boundary layer on the solid wall surface by disposing refractory as a spacer. The material being heated against the flow is more effective than constructing the furnace with simple plane walls. Furthermore, the obstacles in the flow often work as heat accumulators and can be used as wavelength conversion bodies, which are discussed later, although it is difficult to estimate the convection heat transfer coefficient in a complicated flow.

1.2.3.2 Radiant Heat Transfer of High Temperature Air Combustion

The uniformity of temperature distribution comes from the dispersed reaction zone accompanied by a relatively mild temperature rise because combustion air or fuel is diluted with burned product before combustion. Accordingly, the reaction rate decreases, resulting in a long flame or a reaction zone if it is invisible. Generally, the length of a turbulent jet flame is kept nearly constant, because the momentum increase of a fuel jet generates enhanced mixing by entraining larger amounts of surrounding air. However, under low oxygen concentration atmosphere, the flame length will increase by the decreased reaction rate. Example calculations predict a