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HIGH TEMPERATURE AIR COMBUSTION

FROM ENERGY CONSERVATION TO POLLUTION REDUCTION

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High Temperature Air Combustion: From Energy Conservation to Pollution Reduction
Hiroshi Tsuji, Ashwani K. Gupta, Toshiaki Hasegawa, Masashi Katsuki, Ken Kishimoto, and Mitsunobu Morita

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.

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