Pulverized Coal Combustion

Recent Developments

Stanley Singer

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Foreword

This comprehensive, in-depth review of recent developments in pulverized coal combustion technology covers the state of the art, recent technical progress, and future research needs, based on extensive literature reviews and discussions with authoritative engineers and scientists in the field. The book also details ongoing research sponsored by the U.S. Department of Energy at numerous universities, nonprofit research institutions and industrial laboratories.

Pulverized coal combustion achieved increased significance during the recent energy crises, and it continues to challenge our understanding of processes and technologies associated with energy utilization.

The chapters in the book present the major topics of pulverized coal combustion in the order of processes that solid particles undergo, as they approach combustion, ignite, and burn. First, the composition and structural properties of *solid* coal are described, followed by a discussion of the properties of fuel *particles*. Heat transfer, precombustion transformations, and the complex mixture of volatiles formed on combustion of the fuel particles are discussed next. The review then considers the effects of small solid particles in the combustion zone and on the fluid dynamics of the process, and the role of radiation in energy transfer in flame processes. Finally, control of combustion to minimize pollutant formation, from nitrogen- and sulfur-containing substances in the coal, is detailed, as are soot and ash formation.

The information in the book is from *Pulverized Coal Combustion,* by Stanley Singer, The Engineering Societies Commission on Energy, Inc. (ESCOE), for the U.S. Department of Energy, April 1983.

The table of contents is organized in such a way as to serve as a subject index and provides easy access to the information contained in the book.

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NOTICE

Contents and Subject Index

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Prologue

1.1 INTRODUCTION

The Engineering Societies Commission on Energy, Inc. (ESCOE) is a non-profit corporation established at the request of the U.S. Government by the five Founder Engineering Societies to provide objective technical and economic assessments of existing and emerging energy technologies required to meet changing national needs.

The work activities of the group are organized into the ESCOE Engineering Program. The professional staff at ESCOE consists of Engineers and Scientists in Residence who are on leaves of absence from their employers in industry and academia. These individuals are selected for 18- to 24-month tours of public duty on the basis of records of experience and achievement related to the ESCOE Engineering Program.

ESCOE technical reports are reviewed prior to publication by peers appointed to this task by the Founder Engineering Societies and cognizant representatives of the client.

1.2 OBJECTIVE

In February, 1982, under the technical direction of the Pittsburgh Energy Technology Center (PETC) — the lead organization in the Department of Energy for coal research — ESCOE undertook a task to review the current state of pulverized coal combustion (PCC) and synfuel utilization (SU) and to examine the adequacy of the PETC program in covering the significant areas of these fields.

The combustion of pulverized coal is a research area of recently increased significance which continues to challenge our understanding of processes and technologies associated with the utilization of energy. The problems encountered in use of this fuel in particular have practical implications related to down-time of utility furnaces and derating of generator power levels. Many significant technical organizations including universities, non-profit research institutions, and industrial laboratories are engaged in the DOE/PETC PCC program.

This report is limited to the PCC portion of the ESCOE task. The principal objective of our study is (1) to give a comprehensive, in-depth review of the field of pulverized coal combustion covering essential background, recent technical progress, and research needs, and (2) to provide an objective assessment of the current DOE/PETC PCC program.

1.3 REPORT CONTENT AND ORGANIZATION

This report focuses on pulverized coal, the major such fuel presently in use. It is based on a review of the literature and discussions with authoritative engineers and scientists in specific subjects. The evaluation of the field of pulverized coal combustion is followed by an assessment of the DOE/PETC PCC program with consideration given to whether significant problems which were identified in the course of the review are represented.

The material on heterogeneous combustion of fine particles is taken up in the order of the processes which the solid particles undergo as they approach the combustion zone and subsequently enter it, ignite, and burn. This order is followed in the reviews of both the literature and the PCC program.

First, the composition of the solid phase and its structural properties are considered. Then, the specific properties of the fuel particles are discussed. As the particles approach the combustion region, heat transfer increases the fuel temperature, causing precombustion transformations and emission of a complex mixture of volatile substances from the fuel particles (devolatilization). These processes are discussed next.

The review then considers the presence of small solid particles in the combustion zone and their contribution to specific effects absent in homogeneous gas flames. The role of radiation in energy transfer in flame processes becomes much more significant, particularly when the fuel is coal or char. The solid particles also affect fluid dynamics.

Discussion then proceeds to substances containing sulfur and nitrogen which are part of the complex composition of coal. Combustion of these substances must be controlled to minimize formation of pollutants. Pollutants arising from the nitrogen components are controlled through the processes of staged combustion.

Incomplete combustion of the fuel can occur when fuel-rich regions with insufficient oxygen are present in the combustion zone, a condition especially liable to be present in staged combustion. The formation of soot, which may be enhanced under fuel-rich conditions, is reviewed. The final subject is ash formation; the inorganic mineral content of coal eventually resides in this material after combustion.

In this evaluation of the field the literature published in the technical journals was a major resource. The primary references in the scientific and technical literature concerning the combustion of coal number over one thousand. Two major monographs deal at length with coal and its combustion: the four-volume Chemistry of Coal Utilization and Pulverized Coal Combustion and Gasification. There are over a half-dozen extensive reviews in the recent literature which consider significant specific subjects at length. Such secondary sources provide the bulk of citations in the discussion of the field work spanning a significant period of time. On current advances, recent primary papers are cited.

It is evident that there is a large quantity of basic information to consider. There is general agreement on what the major parameters in coal combustion are, but a comparison of the authoritative reviews shows that despite the mass of data available there are few questions which have been answered conclusively, from the combustion of the simplest coal volatile substance (for example, methane) to the chemical structure of coal itself. The treatment of such long-standing problems as the role of strong turbulence in coal combustion varies markedly even among authorities. Adequate presentation of a number of these topics in a limited space encounters practical obstacles. Selective limitation of the material presented has been necessary.

1.4 CONCLUSIONS

- Industrial use of pulverized coal and combustion technology is old and widespread.
- Previous literature studies of pulverized fuel combustion are numerous and cover several problem areas.
- Significant discontinuities in the understanding of pulverized coal combustion exist in the following areas:
  - chemical coal structure (CCS)
  - effect of CCS on pyrolysis and combustion
  - physical structure of solid phase
  - heat transfer and fluid dynamics
  - combustion process mechanisms and kinetics
  - devolatilization
  - sulfur and nitrogen control
  - soot and coal ash
- Incomplete understanding of pulverized fuels is a potential barrier to industrial applications which may emphasize combustion and pollution control, soot and ash control, fuel versatility, heat utilization, and furnace design.

- The DOE/PETC Pulverized Coal Combustion Program supports a well-balanced slate of basic research studies in almost all major problem areas in the field.

1.5 RECOMMENDATIONS

- The DOE/PETC PCC Program review meetings and evaluation procedures should continue on a regular basis to assure the high quality of individual projects and the technical needs of the program as a whole.

- Additions to the DOE/PETC PCC Program should be considered in the areas of

  — soot formation
  — combustion turbulence
  — combustor energy efficiency

- Novel, incisive studies of combustion-oriented problems in the areas indicated above and in other areas, as appropriate to the program, having a bearing on future practical applications of pulverized coal should be given early priority.

2

Background and History

Coal is the fuel used in largest amounts in pulverized form for practical applications. However, a number of other solid materials are available and have been used in powdered form for specialized applications. Among these are finely powdered metals: aluminum, boron, and zirconium.[16] For example, aluminum powder is used in the space shuttle propellant.

The use of pulverized coal in industry is approaching the century mark. The development of pulverized coal technology is an interesting episode in industrial advances concerned with widely used, large-scale process equipment. In the last decade of the nineteenth century pulverized coal began to be used in the cement industry in heating drying kilns, but the methods were a well kept industrial secret. Pulverized coal is still used on a large scale in this industry after some intermittent usage of oil and gas as the economics of the fuels varied. A 1500-hp ball mill with dimensions of 13' x 19' capable of grinding 36 long tons of coal per hour for this purpose is shown in Figure 1. The particles are usually classified by passage through a 200 standard mesh screen resulting in a size range of approximately 1-100 μm. The long residence time and relatively moderate heat requirement of the drying kilns were factors aiding successful utilization of the fuel at the time. As word of the development spread, in the first decade of this century, studies were initiated in the iron and steel industry in attempts to utilize pulverized coal in metallurgy. Some difficulty was encountered, evidently because there was little development of furnaces designed for the new fuel. Rather, the coal was introduced into existing units and conditions sought for acceptable operation. However, in reverberatory furnaces for copper metallurgy again the ample furnace dimensions gave sufficient residence time for combustion of the particles, and the application proved effective. Smaller metallurgical furnaces requiring high temperature were also successful in utilizing pulverized coal.

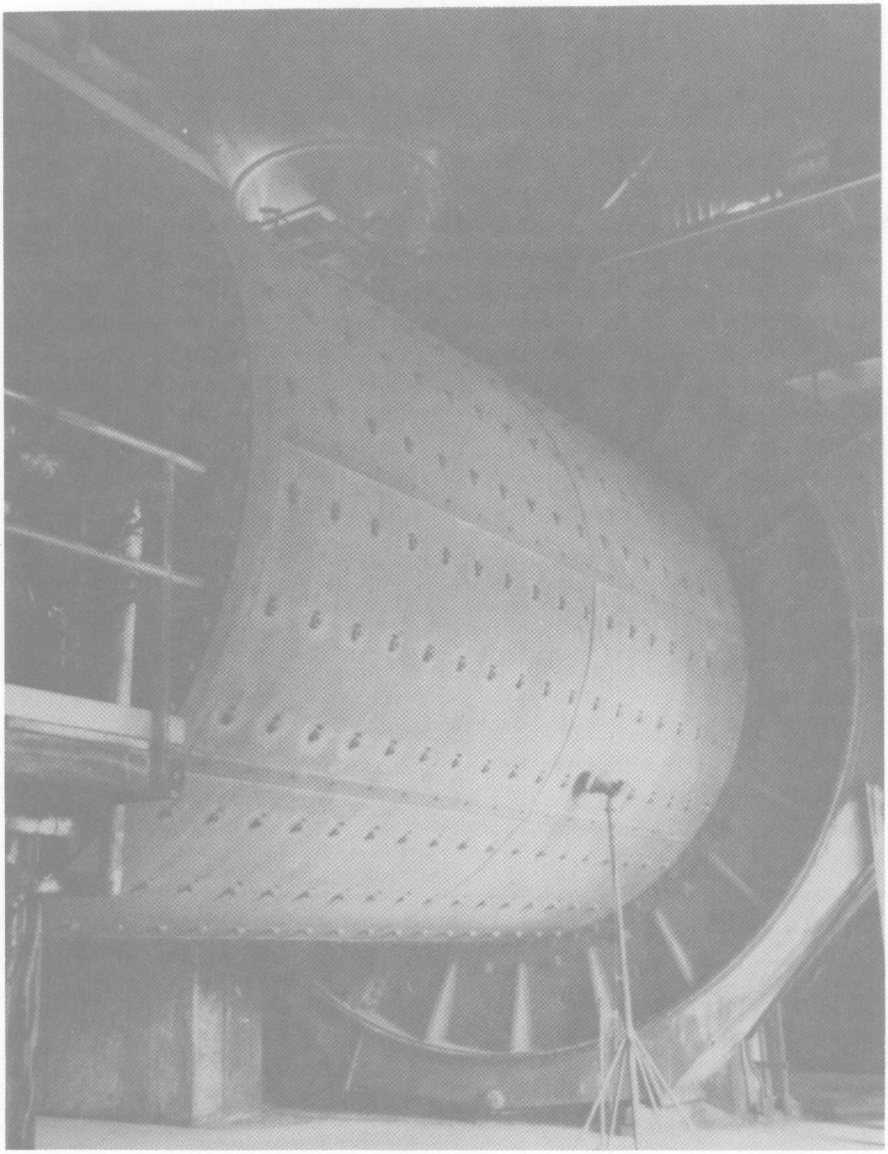

Figure 1. Coal-pulverizing 1500 hp Ball Mill;
dimensions 13' x 19', capacity 36 long TPH

In the second decade of the twentieth century the electric utility industry embarked on successful development of pulverized coal fueled generators by use of furnaces specifically designed for the fuel. By the end of the third decade most of the steam boiler furnaces were operating with pulverized coal.

Several factors were involved in the transition from lump and crushed coal, stoker-fired plants to the new powdered fuel. The electric utility industry was gradually moving from small, uniformly distributed generating plants to large, centralized stations calling for increased generating capacity in individual plants. Pulverized coal, once conditions for practical effective operation had been established, afforded new capability in increased scale and fuel efficiency beyond the limitations of stoker firing while reducing sensitivity to the variations in feed coal. Large industrial steam generators above 250,000 lb/hr steam capacity and coal-fired electric utility plants up to 9,500,000 lb/hr steam (1300 MW) use pulverized coal. Generally, industrial plants requiring relatively low energy still use stoker-firing of the larger coal sizes.

With the recent increase in attention to the nation's coal resources came a reexamination of factors involved in the effective utilization of coal as an energy source. In the area of combustion, significant problems are recognized in such aspects as control of the combustion process, fireside corrosion, ash, and pollution. Such problems exert a practical effect on industrial operations including down-time for maintenance and renovation and derating of operational levels, two not entirely independent factors.

In anticipation of increasing utilization of pulverized coal the DOE Pittsburgh Energy Technology Center initiated a wide-ranging combustion research program with the goal of improving the technology. The studies making up the program have been commissioned at university, industrial, and non-profit research laboratories.

3

Coal and Peat

3.1 FORMATION OF COAL

Coal is without doubt the solid fuel available in largest quantities world-wide for practical use. It is the product of the transformation of plant material subjected to increased temperature and pressure in nature. Of the two the temperature appears more significant. The conversion of the variety of starting materials under a range of conditions over geologic ages led to the formation of products with a wide range of properties. Coal is a distinctive, readily recognizable substance; but it is not a single well-defined chemical compound nor even a homogeneous material. In the United States, Eastern coal is derived from plant substances laid down approximately 250 million years ago; and Western coal, approximately 150 million years later, in accordance with the relative age of the major geological features of the regions involved.

The material produced has been subdivided according to its properties into several classifications which are associated with the degree of transformation: peat, Brown Coal, lignite, subbituminous, bituminous (subdivided into three types: high volatile, medium volatile, and low volatile), and anthracite. The substances so named represent progressive stages in the transformation of plant matter into coal. The range of substances indicated begins with the formation of peat by combined physical, chemical, and biological processes. Overcovering of the peat and its exposure to increased temperatures then gives rise to the changes referred to as coalification. The role of geologic pressures in the transformation is not widely accepted. The presence of natural radioactive materials such as uranium can also bring about coalification, although this occurs rarely.

Peat is usually not included within the range of materials designated coal. It is a preliminary stage in the formation of coal but is itself a fuel of wide use. The plant matter from which it is derived has been undergoing conversion for the shortest period of time, one million years or less.[21] Plants are saturated or submerged under water, and with aging the relative carbon content increases while water, carbon dioxide and perhaps methane are gradually released. The material formed is yellow to dark brown in color and still contains fibrous material. Peat as obtained from the bog and drained of excess moisture contains up to 95% water. Air drying can reduce the water content to approximately 50%. Heating raw peat under pressure, injection of steam, or addition of oxygen aids in separating the strongly bound water. Reduction of the moisture content to 50% or less gives a fuel releasing up to 5000 Btu/lb.

The large resources of peat world-wide encourage consideration of its use as a fuel and, recently, as a raw material for gasification. The Soviet Union uses 95% of the total amount consumed in the world. Ireland, Germany, and Finland obtain significant portions of their total energy supply from peat although their total use of peat amounts to only a few percent of the world total. Some of the significant properties of coal and peat are compared in Table 1.

3.2 COAL RANKS

The rank designations in Table 1 indicate degrees of coalification. The properties of the substances listed change in a continuous manner from the top to the bottom of the Table. This is the order in which the coal rank is said to increase. The following changes are evident. Moisture content decreases with increasing rank. Carbon content increases. Oxygen decreases. The percentage of hydrogen remains relatively constant in the lower rank coals and then decreases in the highest rank coals. Density increases with rank after a small minimum occurring in medium volatile bituminous coals of approximately 85% carbon.[21] The amount of volatile material, determined by heating the coal after it is dried, diminishes with coal rank. The heat released