Erich Raask

Mineral Impurities In Coal Combustion

Behavior, Problems, and Remedial Measures

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FOREWORD

Mineral matter has always been the nemesis of coal-burning industries. Since the dawn of the industrial revolution, the "impurities" in coal have had a major effect on the design of boiler furnaces and how they are operated. An estimated 100 million tons of mineral matter, converted to "coal ash," will pass through the pulverized-coal-fired boiler furnaces in the United States in 1984. The worldwide figure is less certain. This huge mass of troublesome material will lead to some of the most serious operational problems facing the utility industry, and it will cost the industry tremendously in capital investments and in availability because of ash-limited generation. In industrial applications, too, clinker formation in fixed-fuel beds, as in stokers, will continue to limit burning rates, just as it has done for more than a hundred years. In the huge utility-operated, pulverized-coal-fired units, slagging will still be a major determinant in fixing furnace size, and hence relative cost, for a given output of steam, just as it has done since 1920. Fouling in these same steam generators will dictate the spacing and the location of convective tube banks for superheating and reheating steam. In short, the mineral matter in coal continues, as it always has, to be a dominating factor in deciding on the dimensions of boiler furnaces for a given steam output; in proportioning the heat-receiving surfaces for design steam production and properties; in setting limits for flue-gas velocity and flow patterns to minimize metal loss by erosion; and in influencing the physical and chemical properties of the fly ash leaving the stack to ensure its capture by emission-control systems.

It is the mineral matter in coal that plays the dominant role in fuel selection, in setting the design and size of the furnace, and in establishing how that boiler furnace will be operated.

The literature on steam generation in coal-burning boiler furnaces is replete with accounts of operational problems with coal ash. Perhaps there are as many as 5000 published technical papers in the literature, by or aimed mainly at mechanical engineers, covering some aspect of coal-ash behavior in large boiler furnaces. These range from highly technical accounts by specialists in coal-ash behavior to generalized summaries by power-plant operating personnel. Chemists and physicists have contributed, too, but engineering approaches are more common. Yet with all this effort for at least half a century, few comprehensive reviews have been published covering the field adequately that lack bias, are technically sound, and yet are expressed in terms meaningful to a fuels-technology specialist as well as to the mechanical engineer charged with operating and maintaining a power plant. This book, written with a background of a quarter century in solving problems brought about by coal ash in large boiler furnaces, and yet covering the chemistry and physics of ash behavior, will aid tremendously in closing the gap between "practice" and "research."

The state of the art in this field has been based largely on empiricism, even though science and theory have been applied in a widely varying degree. For example, determining the fusibility of coal ash, a basic property in assessing coal behavior, as done most commonly has little relation to the rheology of silicate systems. And yet this basic property of ash at high temperatures almost certainly must influence the thickness of slag on heat-receiving surfaces and so affect heat transfer. Hence, applying empirical measurements to predict the behavior of an unfamiliar coal in a given boiler furnace can be unreliable–and often is. Yet the more technically sound methods of measuring fundamental flow characteristics of coal-ash slags has not contributed much as yet to predicting ash behavior, except under limited conditions. It has been realized for many years that ash characteristics must be related to boiler configuration and to operating conditions in assessing the likelihood of ash-related problems, yet such three-pronged studies are few, and generalized relationships are not yet available. Perhaps the growing realization that coal will be our main source of energy for generating electricity for the coming century will lend emphasis to our need for more basic information on coal-ash behavior under real-life conditions.

This book will go far in satisfying that need. Erich Raask brings to it a quarter century of experience in day-to-day laboratory research on fuel-ash problems and operating experience in large generating plants, coupled with the expertise of a science graduate. He is well known in engineering circles for his extraordinary ability to couple technology and practice. He has the respect of his peers. The detail he provides here on the mineral matter in coal, on the behavior of these minerals during combustion, on the bonding of slag to boiler surfaces, and on the great number of operational problems resulting from coal ash in boiler furnaces will be as remarkably helpful to researchers in this field as to the engineers who plan and operate large power plants.

Texts of this scope and this wide coverage on this important subject are few indeed. This one will serve well for many years.

William T. Reid
Battelle Columbus Laboratories, Columbus, Ohio

PREFACE

The principal aim in writing this book was to present information on many and varied boiler operation problems associated with coal mineral impurities in a form that should assist plant design and operation engineers in their endeavor to produce electrical energy from coal with a maximum efficiency. Also, it is hoped that young scientists and engineers who are embarking on careers in the field of energy sciences and application may find the book useful in bridging the gap between research findings and practical requirements.

The book is based largely on the author's own work in the field of coal utilization research, extended over a period of 25 years. The continuity and scope of the author's experience, which includes both laboratory research and plant investigations, together with a selection of the more significant published data from literature, should serve as a review of various difficulties encountered in operation of coal-fired boilers.

The author would like to record his appreciation and gratitude to scientists, fuel technologists, and engineers whose work has been referred to in this book. Further, it has been the author's privilege to meet and talk to many research workers and boiler-plant design and operation engineers whose names are not recorded in the book. The author is greatly indebted to them for much valuable information and for insight into a variety of the problems encountered at coal-fired power stations.

The author received from his colleagues valuable comments, corrections, and suggestions for changes that have been incorporated in the text. However, the choice and arrangement of the subject matter and the opinions expressed in the book rest solely with the author.

Erich Raask

NOMENCLATURE

SYMBOLS OF SI UNITS AND CONVERSION TO OTHER UNITS

Basic SI Units

1 meter (m) = 3.28 ft
1 kilogram (kg) = 2.205 lb
1 tonne (t) = 1 Mg = 2205 lb = 0.984 long ton = 1.102 short ton
1 second (s)
1 kelvin (K) = 1°C = 1.8°F
1 ampere (A)
1 mole (mol) = 6.02×10^{26} molecules
1 radian (rad) = 57.3 angular degrees (°)

Derived SI Units

Area: 1 m^2 = 10.76 ft^2
Volume: 1 m^3 = 10^3 liter (l) = 35.3 ft^3 = 264 U.S. gal = 220 U.K. gal
Density: 1 kg m^{-3} = 0.0624 lb/ft
Force (Newton): 1 N = 1 kg m s^{-2} = 10^5 dyne = 0.2248 lbf
Pressure (Pascal): 1 Pa = 1 N m^{-2} = 10^{-5} bar = 1.45×10^{-4} psi
Energy (Joule): 1 J = 1 kg m^2 s^{-2} = 10^7 erg = 0.239 cal = 0.738 ft lb = 9.48×10^{-4} Btu
Power (Watt): 1 W = 1 J s^{-1} = 10^7 erg s^{-1} = 0.86 kcal/h = 1.34×10^{-3} hp = 3.41 Btu/h
Combustion intensity (heat relase): 1 W m^{-3} = 0.0967 Btu/ft^3 h

Heat flux: 1 W m^{-2} = 0.317 Btu/ft^2 h
Heat transfer coefficient: 1 W m^{-2} K^{-1} = 0.176 Btu/ft^2 h °F
Thermal conductivity: 1 W m^{-1} K^{-1} = 0.578 Btu/ft h °F
Calorific value: 1 KJ kg^{-1} = 0.239 kcal/kg = 0.430 Btu/lb
Specific heat capacity: 1 J kg^{-1} K^{-1} = 2.39 × 10^{-4} cal/g °C = 2.39 × 10^{-4} Btu/lb °F
Entropy: 1 J K^{-1} = 0.239 cal/°C^1 = 5.27 × 10^{-4} Btu/°F
Dynamic viscosity: 1 N s m^{-2} = 1 Pa s = 2420 lb/ft h
Kinematic viscosity: 1 m^2 s^{-1} = 3.88 × 10^4 ft^2/h
Surface tension: 1 N m^{-1} = 10^3 dyne/cm
Electrical potential: 1 V = 1 W A^{-1}
Electrical resistance: 1 Ω = 1 W A^{-2}
Electrical resistivity = 1 Ω m = 3.28 Ω A
Electric field strength = 1 V m^{-1} = 0.305 V ft^{-1}
Electric conductance: 1 siemen (S) = 1 Ω^{-1}
Electric conductivity: 1 S m^{-1} = 0.305 Ω^{-1} ft^{-1}
Periodic frequency = 1 hertz (Hz) = 1 s^{-1} = vibration/s
SI Factors printed before basic units: exa (10^{18}), E; peta (10^{15}), P; tera (10^{12}), T; giga (10^9), G; mega (10^6), m: kilo (10^3), k; milli (10^{-3}), m; micro (10^{-6}), μ; nano (10^{-9}), n; pico (10^{-12}), p; femto (10^{-15}), f; atto (10^{-18}), a

Conversion of Other Units to SI Units

Length: 1 foot (ft) = 12 in = 0.305 m
Mass: 1 pound (lb) = 0.4536 kg
1 short ton = 2000 lb = 0.907 tonne (t) = 907 kg
1 long ton = 2240 lb = 1.016 tonne (t) = 1016 kg
Area: 1 ft^2 = 0.093 m^2
Volume: 1 ft^3 = 0.0283 m^3 = 28.3 l (liter)
1 U.K. gal = 1.201 U.S. gal = 4.546 l = 0.004546 m^3
1 bbl = 159 l = 0.159 m^3
Density: 1 lb/ft^3 = 0.134 lb/U.S. gal = 0.1605 lb/U.K. gal = 16.02 kg m^{-3}
Force: 1 lbf = 4.44 N
Pressure: 1 atm = 101.3 kPa
1 psi = 6.895 kPa
1 in wg = 249 Pa
1 torr (mmHg) = 133 Pa
Temperature: 1°F = 0.5556°C = 0.5556 K
Energy: 1 Btu = 10^{-5} therm = 1.055 kJ
1 ft lbf = 1.355 J
1 tce = 1 tonne coal equivalent = 28.8 GJ
Power: 1 Btu/h = 0.293 W
1 hp = 0.745 kW
Combustion intensity: 1 Btu/ft^3 h = 10.35 W m^{-3}
Heat flux: 1 Btu/ft^2 h = 3.155 W m^{-2}
Heat transfer coefficient: 1 Btu/ft^2 h ° F = 5.675 W m^{-2} K^{-1}
Thermal conductivity: 1 Btu/ft h °F = 1.731 W m^{-1} K

Calorific value: 1 Btu/lb = 2.326 kJ kg^{-1}
1 Btu/ft^3 = 37.26 kJ m^{-3}
Specific heat capacity: 1 Btu/lb °F = 4.187 kJ kg^{-1} K^{-1}
Dynamic viscosity: 1 lb/ft h = 0.413 mPa s
1 cP = 1 mPa s
Kinematic viscosity: 1 ft^2/h = 25.8 mm^2 s^{-1}
1 cSt = 1 mm^2 s^{-1}
Surface tension: 1 dyne/cm = 10^{-3} N m^{-1}
Electrical resistivity: 1 Ω ft = 0.305 Ω m
Electric field strength: 1 V/ft = 3.28 V m^{-1}
Electric conductivity: 1/Ω ft = 3.28 S m^{-1}

Temperature Conversion

$$°F \longleftarrow K \longrightarrow °C$$
$$(1.8x - 459.67)°F = xK = (x - 273.15)°C$$

$$°F \longrightarrow K \longleftarrow °C$$
$$y°F = (0.5556y + 255.15)K;\ (z + 273.15)K = z°C$$

GLOSSARY OF INSTITUTIONS

ASTM	American Society for Testing Materials, Philadelphia, Pennsylvania
BCURA	British Coal Utilization Research Association, Leatherhead, U.K.; now part of the National Coal Board, London, England
CEGB	Central Electricity Generating Board, London, England
CSIRO	Commonwealth Scientific and Industrial Research Organization, Sydney, Australia
DIN	Deutsche Industrie Normen (German Industry Standards), West Berlin, Germany
EPA	Environmental Protection Agency, Washington, D.C.
EPRI	Electric Power Research Institute, Palo Alto, California
IGT	Institute of Gas Technology, Chicago, Illinois
JANAF	Joint Army, Navy, Air Force Thermochemical Data Bank, Washington, D.C.
NCB	National Coal Board, London, England
VGB	Vereinigung der Grosskraftwerksbetreiber (Association of Power Generation Undertakings), Essen, West Germany

CONTENTS

CHAPTER

ONE

INTRODUCTION

In the 1960s coal was losing ground as the principal primary fuel for electricity generation. Oil was plentiful and cheap, and nuclear power appeared to be poised for rapid growth. By the mid-1970s the fuel situation had undergone a drastic change. The price of liquid fuel had increased sharply and, with the exception of the oil-exporting countries, hardly any new oil-fired power stations have been built anywhere else since that date. It was inevitable, therefore, that there should have been renewed interest in utilizing coal for power generation. A number of countries are currently planning to exploit new coal fields for their own use and for export. Some countries where there are no significant deposits of indigenous coal, notably Japan and the Scandinavian countries, are in the process of building up a substantial electricity-generating capacity based on imported coals. Future coal prospects on a world wide basis have been assessed in the *Report of World Coal Study*, edited by Greene and Gallagher (1980), and by Ion (1980).

More extensive use of solid fuel for power generation will accentuate the boiler operation problems associated with mineral impurities in coal, and there is a need for a comprehensive source of information on various difficulties. First, an account is given of changes in the design of coal-fired utility boilers from the small, 1- to 2-MW capacity, stoker-fired boilers to the present-day large pulverized-fuel-fired units of 500- to 1300-MW output. The need for more efficient utilization of fossil fuel has always been the driving force for the large and more economical power plant. However, difficulties caused by coal mineral impurities, in particular those of ash deposits on heat-exchange surfaces, have influenced the changes in boiler design.

In spite of extensive research and the wealth of practical experience there remain some enigmatic aspects in the subject of boiler slagging. For example, the massive build-up of ash deposits can take design and boiler operation engineers by surprise.

The nature of different mineral species of solid fuels, bituminous and non-bituminous coals, and lignite is evaluated in this book. The difficulties of coal grinding and the wear on fuel handling and milling plants are discussed in relation to the abrasive minerals in coal. This is followed by a synopsis of the physical changes and chemical reactions of different mineral species in coal flame; changes and reactions of great importance, not only to formation of boiler deposits but also in relation to other salient properties of ash. These properties are the corrosion propensity of ash, the abrasiveness of ash related to erosion wear of boiler tubes, the electrical resistivity of ash (which is relevant to the efficient working of the electrical precipitators), and the pozzolanic (cementitious) properties of ash when it is used in concretes and in grouts as a cement extender.

The chapters on the flame reactions are followed by discussions on the viscosity as a rate-controlling parameter in ash sintering and fusion, an assessment of the slagging propensity of ashes, the formation and adhesion of deposits in boiler plant, and the effects of boiler deposits on heat transfer. Under the heading of counter measures to combat boiler slagging, the topics discussed are design considerations, combustion control, and conventional and unconventional methods of boiler cleaning. A separate chapter is devoted for discussion on the specific ash-related problems with U.S. low- and high-rank coals. A wide variety of solid fuels is utilized for power generation in the United States, and the deposit-forming characteristics of the lignite and sub-bituminous coal ashes can be markedly different from those of bituminous coal ashes.

The literature on low-temperature additives used to improve the ash capture performance of the electrical precipitators is extensive. In contrast, less information is available on the use of high-temperature additives to combat boiler slagging.

The manifestation of boiler slagging can be immediate, and large quantities of ash deposits can form in the combustion chamber within a few hours, whereas boiler tube corrosion is usually a long-term event determined largely by the "quality" rather than by the quantity of the fuel impurity deposit. The mode of formation of potentially corrosive deposits of molten alkali-metal sulfates is discussed, followed by an assessment of the corrosion propensities of different coals.

High-temperature slagging and corrosion by ash deposits cease to be serious problems in the middle section of boiler plant, but the economizers and the hot sections of air heaters can be plugged by the high-temperature deposit debris and ash compacts. There is another problem that occurs in this boiler section, namely, the tube erosion wear by ash impaction when the impact velocity exceeds that compatible with the abrasive property of ash. In this book the abrasive property of ash in different coals will be discussed with the intention of helping design engineers to arrive at an optimum velocity for the ash-laden flue gas in boiler ducts without causing significant erosion wear.

Condensation of sulfuric acid in air-heaters and in chimneys of pulverized-coal-fired boilers constitutes a lesser problem than it does in residual oil-fired boilers.