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Thermal efficiency of coal-fired power plants: From theoretical to practical assessments

Chao Fu [a,*], Rahul Anantharaman [b], Kristin Jordal [b], Truls Gundersen [a]

[a] *Department of Energy and Process Engineering, Norwegian University of Science and Technology, Kolbjorn Hejes v. 1A, NO-7491 Trondheim, Norway*
[b] *SINTEF Energy Research, Kolbjorn Hejes v. 1A, NO-7491 Trondheim, Norway*

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ABSTRACT

The improvement in thermal efficiency for coal to power processes is increasingly important due to concerns on CO_2 emissions. This paper presents a systematic study on direct combustion coal to power processes with respect to thermodynamic, technical and economic factors. Traditional exergy analysis focuses on irreversibilities in existing processes, while the new methodology investigates the thermal efficiency from its theoretical maximum to practical values by adding irreversibilities one by one. As a result of the study presented in this paper, various measures for increasing the thermal efficiency are investigated and the corresponding improvement potential is presented. For a reference power plant, the exergy of the coal feed is calculated to be 1.08 times the lower heating value. The actual thermal efficiency is 45.5%. The irreversibilities are caused by the combustion reaction, heat transfer between flue gas and water/steam, low temperature heat losses, the steam cycle, and other factors. Different measures to increase the thermal efficiency of the reference plant by 0.1% points are presented. The minimum thermal efficiency penalty related to CO_2 capture is 2.92–3.49% points within an air factor range of 1.0–1.4 when the CO_2 is 100% recovered.

1. Introduction

Coal will continue to be a dominant energy source also in the next decades. It was responsible for 41% of the world power generation in 2012 and is projected to be around 31% in 2040 [1]. Coal-fired power plants have been in continuous development for more than 100 years with considerable efforts to improve the capacity and thermal efficiency. The plant thermal efficiency has increased continuously from around 5–45% in the past century [2]. Reducing cost for power generation has always been a motivation for efficiency improvement. The increasing concerns about CO_2 emissions stimulate further improvements in thermal efficiency. In direct combustion coal to power processes, the chemical energy of coal is converted into heat and this heat is further converted into power. Considerable efforts have been made to improve the thermal efficiency, such as reducing the irreversibilities in the process that converts the chemical energy of coal into heat [3], maximizing power production from the heat [4] and minimizing the losses of low temperature heat [5]. For pulverized coal-fired power plants, the long-term target for thermal efficiency is above 55% by using steam with maximum temperatures around 1073 K (800 °C) [5].

The thermodynamic principles of coal-fired power plants (mainly steam cycles) have been described in many textbooks related to thermodynamics and power technologies [5–10]. Various measures for improving the plant performance have also been presented in these books as well as in many other publications. Previous studies on the performance assessment are mostly based on detailed process modeling, thermodynamic analysis and parameter sensitivity analysis. Aljundi [11] performed a detailed study of an existing power plant using both energy and exergy analyses. The energy and exergy efficiencies were used to investigate the performance of individual unit operations. Zhang et al. [12] performed a thermos-economic analysis of a coal-fired power plant using process simulation and exergy analysis. Olaleye et al. [13] used exergy analysis to investigate the performance of a supercritical coal-fired power plant with and without CO_2 capture. Distribution of exergy losses among the sub-units was presented. A coal-fired ultra-supercritical power plant was evaluated by Yang et al. [14] using exergy analysis. The exergy destruction is split in two ways: (1) avoidable and unavoidable parts, and (2) endogenous and exogenous parts. Vučković et al. [15] performed a similar study on a steam boiler using the two different ways of exergy splitting.

The above studies [11–15] require detailed process data in order to perform thermodynamic analyses. The influence of

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[*] Corresponding author. Tel.: +47 73592799.
E-mail addresses: chao.fu@ntnu.no, fuchao83@hotmail.com (C. Fu).

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Nomenclature

$\dot{E}$	exergy, kW
e	specific exergy, kJ/kg or kJ/mole
$\dot{F}$	molar flow, mole/s
f	air factor
$\dot{G}$	Gibbs free energy, kW
$\dot{H}$	enthalpy, kW
h	specific enthalpy, kJ/kg or kJ/mole
$\dot{I}$	irreversibility, kW
$\dot{m}$	mass flow, kg/s
p	pressure, bar
$\dot{Q}$	heat, kW
$\overline{R}$	universal gas constant, kJ/(mole K)
$\dot{S}$	total entropy, kW/K
s	specific entropy, kJ/(kg K)
T	temperature, K or °C
$\dot{W}$	work, kW
x	molar fraction

Greek letters

Δ	symbol of differences
η	efficiency
φ	ratio of the chemical exergy to the lower heating value
ω	stoichiometric ratio for combustion

Subscripts and superscripts

0	reference state
ad	adiabatic
C	combustion; cold end
ch	chemical
eco	economizer
FG	flue gas
fw	feed water
H	hot end
i	component index
is	isentropic
j	phase index
min	minimum
mix	mixing
ms	main steam
ph	physical
pre	preheater
RH	reheating steam
SC	steam cycle
tot	total

Abbreviations

BFW	boiler feedwater
CLC	chemical looping combustion
ESP	electrostatic precipitator
FFWT	final feedwater temperature
FGD	flue gas desulphurization
HHV	higher heating value
HP	high pressure
IP	intermediate pressure
LHV	lower heating value
LP	low pressure
MS	main steam
ORC	organic Rankine cycle
RH	reheating
S	superheated
SCR	selective catalytic reduction

process parameters on thermal efficiency was investigated in a quite small operating range. Le Moullec [16] studied the thermodynamic limitations of CO_2 capture on the thermal efficiency of power plants. Three common CO_2 capture alternatives were investigated: post-combustion, pre-combustion and oxy-combustion. The theoretical efficiency penalty related to CO_2 capture was presented. Other factors related to technology and economic factors were not included. Anantharaman et al. [17] presented a new benchmarking methodology for evaluating CO_2 capture processes. The comparison of various capture routes is performed with respect to thermodynamic, technical and economic factors. Detailed introduction to this methodology is presented in Section 2.

The methodology developed by Anantharaman et al. [17] is applied in this paper. The primary objective is to investigate the improvement potential in thermal efficiency and the corresponding limitations for such measures presented in literature. The paper is an extension of the work by Fu et al. [18]. The study starts by calculating the maximum thermal efficiency for a specific coal feed in an ideal (reversible) power plant. This efficiency will decrease when realistic (irreversible) unit operations are added for the combustion process, the heat transfer process, the steam cycle, and the flue gas treatment (CO_2 emission control). The thermodynamic losses (irreversibilities) are caused by spontaneous processes such as combustion, as well as heat transfer at finite (often large) temperature differences, mixing, and turbo-machinery inefficiencies. In addition, the thermal efficiency is limited by technical and economic factors, such as excess air for combustion, maximum pressure and temperature of the main steam, and low temperature heat losses.

Compared to previous work on the assessment of coal-fired power plants, detailed process modeling or plant data are not required in this study. All the limiting factors on thermal efficiency are identified in a systematic way. The improvement potential by various measures can easily be determined. Further, the process parameters can be investigated in a large operating range. For the reference plant, the measures for increasing the thermal efficiency by 0.1% points are investigated. The minimum energy penalty with respect to thermodynamic limitations for capturing CO_2 at various purities and recovery rates is also studied. The results can be used as a basis for evaluating the thermal efficiency of plants where CO_2 capture will be implemented in the future, in addition to the efficiency improvement measures.

2. Methodology

A methodology for benchmarking and identifying improvement potentials of processes was presented by Anantharaman et al. [17]. The motivation for the new methodology was to develop a systematic and consistent way to identify improvement potential and integration opportunities in power processes with CO_2 capture. To this end, three efficiencies that can be specified for a process are [17]:

(1) Thermodynamics limited: This is a scheme that requires the thermodynamically lowest possible energy input to produce the specified energy output. The resulting efficiency is the “ideal” efficiency that is the thermodynamically maximum attainable for such a process. This efficiency can never be