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Power plant fuel consumption rate during load cycling

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HIGHLIGHTS

- The fuel consumption rate during the load cycling is experimentally determined.
- The experimental method of fuel consumption rate online measurement is introduced.
- The method is validated by performing large-scale tests on a 200 MW_{el} power unit.
- The relative changes in fuel consumption rate are compared to previous studies.

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ABSTRACT

A major challenge in the modern power system is the load cycling (ramping down and up) of thermal power plants due to the increase in electricity production from renewable power plants and other sources. The motivation for this paper is to quantify the effect of this on fuel consumption and as a result, variable costs. In this study, an experimental method for determining the fuel flow rate and corresponding power unit characteristics in a load-ramping operating regime was introduced and experimentally tested. The method is based on the static pressure drop of flue gas flowing through some convective heating surfaces of a boiler being proportional to the gas velocity, that is, in turn, proportional to the mass fuel rate. Therefore, after measuring the pressure drop during a steady-state regime, for example, in a tubular air preheater as the heat surface that is less susceptible to contamination from particle laden gas flow, and at the same time calculating the fuel mass flow rate through an indirect heat balance, the two parameters can be interrelated. The semi-empirical relationship obtained in this way can then be used for determining the actual fuel mass flow rate during transient boiler loads. The proposed method was used to determine the technical and economical characteristics of a pulverized combustion power unit utilizing oil-shale. Large-scale experiments were conducted in a high-pressure pulverized combustion steam generator TP-101, with a rated capacity of 300 MW_{th}. The dual-boiler unit load ramping was constrained to 2.5 MW_{el}/min. The results show that during ramping down the load to 50% maximum continuous rating, the mean fuel consumption decreased by 10%, and during ramp-up back to 100% maximum continuous rating, the mean fuel consumption increased by 14%. The total increase in fuel consumption during ramping cycle at given conditions, was approximately 4%.

1. Introduction

The liberalization of electricity markets, along with an increase in the capacity of wind and solar power plants integrated into power transmission networks over the last decade, have resulted in a highly fluctuating production curve in power plants. Inevitably, increased power variability will require improved energy system flexibility [1–3].

Because of the new requirements of the market, coal-fired power plants that were designed for 6000–8000 h of operation per year must now operate at 1500–3000 full load hours per year. A coal-fired power plant with lower efficiency losses at partial loads will be more effective in an open electricity market [4].

Numerous studies have been performed on the effects that increased production from renewable sources has on conventional power plants [1,5–7]. The number of thermal power plant load ramps in Central and Eastern Europe will increase by 63–181% by 2020, compared to 2013, according to a model where cycling costs were modeled as a function of the recent operating history. The cycling of coal power plants depends on the power plant's location. The model showed it to be more prevalent in Germany and the Czech Republic [5]. In the British system in 2020, mainly gas plants will be subject to ramping as the production from coal plants is presumed to greatly decrease [7].

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Nomenclature

A^d	ash content, as dry fuel (%)
$(CO_2)_m{}^d$	mineral CO_2 content, dry fuel (%)
D	diameter (m)
F	cross-section area of flue gas duct (m^2)
H_S	buoyancy force (N/m^2)
L	length (m)
m	mass (kg)
$\dot{m}_F$	fuel mass flow rate (kg/s)
Q_i^r	lower heating value, as received (MJ/kg)
r	normalized mass flow rate change (%)
Re	Reynolds number (–)
S_t^r	total sulfur content (%)
T	temperature (K)
V_g	flue gas volume per fuel mass (Nm^3/kg)
w	flue gas velocity (m/s)
W_i^r	moisture content, as received fuel (%)
Δm_F	fuel mass flow rate increment (kg/s)
Δp_{st}	static pressure drop (Pa)
Δp^*	modified pressure drop over TAPH (Pa)
$\Delta\tau$	time period (s)
ζ	local resistance factor (–)
λ	Darcy friction factor (–)
ρ	flue gas density (kg/m^3)

Abbreviations

BMCR	boiler maximum continuous rating
HS	heating surface
MCR	power unit maximum continuous rating
MFR	mass flow rate
R	during ramping
STAB	during stable operation
TAPH	tubular air preheater

A wide application of non-dispatchable renewable power plants could also cause power shortages and smart grid models are being developed to avoid this and to reduce peak loads [8,9]. With the number of load cycling operations increasing, the effects of the changing pattern on power plant operations needs to be determined. A study of energy and mass balances of thermal power plants is therefore required. Modeling is often combined with field tests on industrial boilers [10–23] and prediction algorithms and statistical tools are developed [24–29]. These studies are applicable as, for instance, thermal power unit control systems can be modified based on these algorithms [30–33], and start-up processes are optimized taking into account thermal stresses in the boiler [34]. The dynamic simulation models are effective tools for studying and understanding the operating characteristics of power plants to meet and improve the design [35]. The validated results are reliable [36].

The fuel consumption rate variation during load cycling is one of the key technical and economic parameters determining thermal power plant load flexibility. Modeling [37] has shown that considering all cycling costs, including a decrease in rated efficiency loss due to cycling, power unit commitment scheduling can decrease the total cycling cost up to 40%. The motivation for this paper is to propose a method to quantify variable costs to plan plant operation based on this knowledge.

This has not been studied widely, but there are some studies regarding the economic effect that load flexibility has. In [38], a parametric approach was used for the valuation of power plant flexibility options. It was demonstrated that a lower minimum operating load has a higher positive economic impact than a higher load ramp rate. In the model used in this study additional capital and O&M costs during load ramping were taken into account, but not the increase in fuel consumption. A feasible ramp rate increase of 100% (from 3.2%/min to 6.4%/min) for a coal-fired power plant decreases ramping costs by 0.98% but does not change overall profit. A 50% reduction in the minimum load increases ramping costs by 7.49%, decreases start-up costs by 71.43%, and increases profit by 7.11% [38]. In [39], it was found through modeling of a 380 MW_{el} combined cycle unit that 50% faster load variation results in a 52.9% reduction in superheater collectors life and 31.9% reduction in steam drum life. Also, additional start-ups increase material fatigue [40].

In [41], a nonlinear simulation model for conventional steam power plants in an once-through boiler design has been elaborated and validated, with a focus on the fuel grinding process and heat transfer to improve power plant flexibility. In addition, part-load and flexible operation of supercritical coal power plants with carbon capture have been evaluated for conventional and advanced integration options [42].

A model [43] for studying the effect of the high penetration of wind power on thermal power plants in Ireland showed that the efficiency of load-following units would decrease by 11% in 2025 due to part-load operation. Unit efficiency data from earlier studies was used. The efficiency decrease during the process of ramping was not considered as the studies used did not include data on this. Another study based on Ireland's power system evaluated the costs of hot, warm, and cold start-ups of power units [44]. Our paper however focuses specifically on the effect of ramping which these studies do not consider.

There have been a few studies on the effect of ramping/cycling on fuel consumption. In a report by the company Intertek Aptech [45], load following costs for different power plants were presented, based on collected data. The weekly increment in effective heat rate due to adding one start-up-shut-down cycle for a small coal plant was 0.62%, for a large coal plant 0.44%, for a gas-fired steam plant 0.20%, and for a gas-fired aeroderivative gas turbine 0.00% [45]. The study does not disclose the exact method how these numbers were acquired due to commercial reasons. Actual data from plants and undisclosed Aptech's own methodology were combined.

In another study using dynamic model based on data measured during static regimes, it was demonstrated that a load ramp-up of a 660 MW_{el} coal-fired power plant from 50% to 100% of maximum continuous rating increases fuel consumption by 1.3% taking into account the whole cycle, and load ramp-down decreases it by 1.0% [46]. It was presumed that real-time fuel consumption during a transient process is affected by the cycling load rates, heat storage in the working medium and metals and process control of the unit. Specific GSE (Gabinete De Software Empresarial SL) software was used and no measurements in dynamic regimes were made. The disadvantage of using process models are the models' complexity [39]. In most cases, there is not sufficient data on the power plant to set up such a model.

The aim of our paper is to demonstrate a transparent and simple approach that can be used for solid fuel power plants to find fuel consumption during boiler transient mode of operation.

To study the effects of load cycling and test the methodology, a power unit in a large power plant was chosen. The total electricity generation capacity of the plant having similar units is approximately 1600 MW_{el}. The power units in this plant are ramped up and down daily. In case of such a capacity, even a minor relative variation in fuel consumption results in a large total fuel use and environmental impact.

Due to electrical load cycling occurring relatively frequently over a wide range of loads, the duration of the transient load periods becomes quite high compared to the total time of working of the power unit in a steady-state regime. During transient periods the heat rate [45], fuel consumption [46], and emissions [43] of a steam generator deviate from the parameters obtained in steady-state conditions. When the