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A dynamic mathematical model of an ultra-supercritical coal fired once-through boiler-turbine unit ☆

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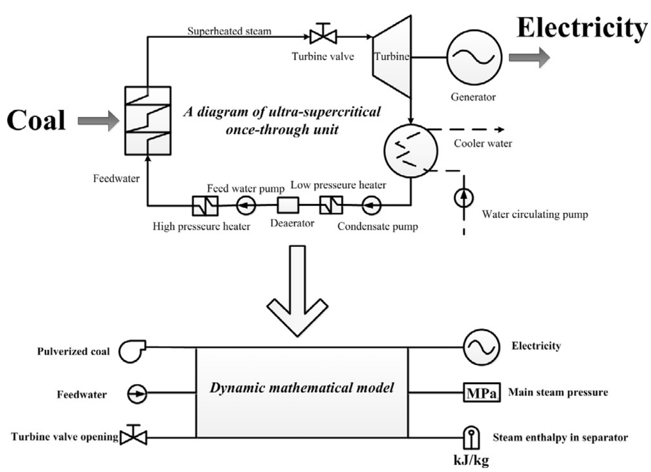
HIGHLIGHTS

- A mathematical model of an ultra-supercritical unit is developed.
- The analysis of open-loop experiments is described.
- Parameter identification based on immune genetic algorithm is presented.
- The closed-loop validation is performed and compared with the previous study.

GRAPHICAL ABSTRACT



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ABSTRACT

It is challenging and interesting to establish a precise dynamic model of an OTB (once-through boiler) power plant unit in order to meet large scale load demands from the power grid. This study proposes to establish such a dynamic mathematical model of an ultra-supercritical OTB unit under dry operating conditions. More precisely, the dynamic model structure was derived from mass and energy conservation laws as well as thermodynamic principles under some reasonable simplifications and assumptions. Then an IGA (immune genetic algorithm) was improved to identify the parameters, combined with running data. After this, to further enhance model performance, the dynamic mathematical model was extended to be the one with different sets of parameters and functions under different monotonous load ranges. Additionally, open- and closed-loop experiments were conducted in order to further validate the developed model. The experimental results show that the model outputs can approach the actual running data over a wide operating range with appropriate accuracy. More importantly, the dynamic model captures the essential dynamic characteristics of the unit. Therefore, the model can be feasible and applicable for simulation analysis and testing control algorithms.

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Nomenclature

u_B	fuel flow rate command (kg/s)
r'_B	mass flow rate of fuel in the mill (kg/s)
τ	delay time of the pulverizing process (s)
r_B	mass flow rate of fuel in the furnace (kg/s)
M	amount of coal in the mill (kg)
c_0	milling inertia time (s)
c_B	output coefficient of the mill
f_H	correction coefficient of the coal grind ability
f_W	correction coefficient of the moisture content of coal
f_R	correction coefficient of coal fineness
p	steam pressure (MPa)
ρ	density (kg/m^3)
D	mass flow rate (kg/s)
h	specific enthalpy (kJ/kg)
T	temperature (°C)
Q_2	heat transferred from tubes to the medium (kJ/s)
ε	drag coefficient
c	specific heat capacity (kJ/(kg·°C))
m	mass (kg)
k_0	the heat released from burning l kg pulverized coal
k_1	the tube constant
k_2	steam turbine gain
n	index coefficient
η	efficiency of the steam turbine
u_t	throttle valve opening($0 \leqslant u_t \leqslant 1$)
N_e	active power (MW)
H_n	heat removed by circulating water (kJ/s)
v_t	total working fluid volume in boiler (m^3)
Q_1	heat absorbed by tube in furnace (kJ/s)

Subscripts

a	average value
in	working fluid in tube
fw	feed water flow
st	throttle steam flow
m	the state in the separator
r	the state in reheater
j	the state in metal
$j1$	the state in metal at outlet of the heated tube
$r1$	the state at inlet of reheater
$r2$	the state at outlet of reheater

Superscript

–	the average value

Abbreviations

OTB	once-through boiler
DBT	drum boiler-turbine
CCS	coordinated control system
IGA	immune genetic algorithm
GA	genetic algorithm

Units

%	percent
MW	megawatt
g/kWh	gram per kWh
kWh	kilowatt hour
kg/s	kilogram per second
t/h	ton per hour
MPa	megapascal
kg/m^3	kilogram per cubic metre
kJ/kg	kilojoule per kilogram
°C	degree Celsius
kJ/s	kilojoule per second
m^3	cubic metre
s	second
kJ/(kg·°C)	kilojoule per kilogram degree
kg	kilogram
kJ	kilojoule
μm	micron

1. Introduction

Coal-fired power plants play a highly significant role in Chinese power generation, even though renewable energy will be rapidly developed in recent years [1]. Meanwhile, it is estimated that the consumption of China's primary energy will reach 4.8 billion tons of standard coal in 2020, and the fossil fuel can account for 70% of the power demand [2]. In the process of coal burning, many air pollutants may be released, namely, sulfur dioxide (SO_2), nitrogen oxides (NOx), and inhalable particle whose diameter is less than 10 μm (PM_{10}), extremely dangerous to human health and the global climate [3–7]. Due to the huge environmental pollution caused by coal burning in every year, Chinese government promises to reduce the CO_2 emission per unit of GDP by 60–65% in 2030, compared with that of 2005 [2]. Therefore, it is a pressing need for coal fired power plants in China to find an effective solution to meet above requirements.

Ultra-supercritical coal fired technology is a considerable option, and owns high operating efficiency and low CO_2 emissions per megawatt (MW) generation. According to the statistical data, the operating efficiency of ultra-supercritical units is beyond 45%, more than around 10% compared with the same level of the current subcritical coal fired units in China. Furthermore, in terms of the environmental protection, the release of CO_2 and SO_2 can be reduced by 145 (g/kW h) and 0.4 (g/kW h), respectively [8]. In addition, the ultra-supercritical unit has faster speed of load response than that of the subcritical unit for less metal content. Nowadays, there are more than eighty ultra-supercritical coal fired plants serving in China, and the plants have prominently significant roles in supplying electricity and maintaining frequency stability of the power network.

Certainly, severe operating conditions have to be in company with a series of technological bottlenecks, such as complex start-up process and less operating reliability. Especially, renewable energy (i.e., wind and solar energy.) will be recently energetically developed due to their non-polluting and sustainable merits [2]. Nevertheless, their unstable and random features may pose a threat to the operating stability of the power grid. Therefore, confronted with these pressures, ultra-supercritical coal fired units are obliged to adjust unit load quickly in order to meet the real-time power demand.

In ultra-supercritical units, the CCS (coordinated control system) is used to solve the above problems. However, for any control systems, the satisfactory control performance is dependent on the accuracy and validity of the process model.

In previous studies, the modelling methods can be roughly summarized into three categories. The first is mechanism modelling, which is developed based on fundamental physical laws so as to master the dynamic behaviours of thermodynamic variables [9–16]. Due to the clear physical structure, the state variables in model are observable. Therefore, this kind of model is also called white box model. After obtaining the model structure, it is neces-