

Modelling Study Of Supercritical Power Plant And Parameter Identification Using Genetic Algorithms

Omar Mohamed, Jihong Wang, Shen Guo, Bushra Al-Duri, Jianlin Wei

Abstract—The paper aims to study the whole process mathematical model for a supercritical coal-fired power plant. The modeling procedure is based on thermodynamic and engineering principles and the previously published literatures. Model unknown parameters are identified using Genetic Algorithms (GAs) with 600MW supercritical power plant on-site measurement data. The identified parameters are verified with different sets of measured plant data. Although some assumptions are made in modeling process, the supercritical coal-fired power plant model reported in the paper can be used to simulate the main features of the real plant once-through boiler operation and the simulation results show the main variation trends of the process.

Index Terms— coal-fired power generation, Genetic Algorithms, mathematical modeling, supercritical boiler.

NOMENCLATURE

ff	Fitness function.
ffr	Fuel flow rate (Kg/s).
h	Enthalpy per unit mass (MJ/Kg).
K	Constant.
k	Mass flow rate gain.
MW	MW power generated.
m	Mass (Kg).
\dot{m}	Mass flow rate (Kg/s).
P	Pressure of a heat exchange (MPa).
\dot{Q}	Heat transfer rate (MJ/s).
R	Response
T	Temperature (C°).
t	Time (sec).
τ	Time constant (sec).
U	Internal energy (MJ).
V	Volume of fluid (m^3).
\dot{W}	Work rate or power (MW).
x	State vector.
y	Output vector.
ℓ	Intermediate variables vector
ϕ	Input vector.
ρ	Density (Kg/ m^3).
\mathcal{N}	Valve opening.
ε	Efficiency.

Subscripts:

ec	Economizer
hp	High pressure turbine
hx	Heat exchanger
i	Inlet

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ip	Intermediate pressure turbine
ms	Main steam
m	Measured
o	Outlet
out	Output of turbine
rh	Reheater
sh	Superheater
si	Simulated
ww	Waterwall

Abbreviations:

ECON	Economizer
GA	Genetic algorithm
HP	High pressure
HX	Heat exchanger
IP	Intermediate pressure
RH	Reheater
SC	Supercritical
SH	Superheater
WW	Waterwall

I. INTRODUCTION

The world is now facing the challenge of global warming and environment protection. On the other hand, the demand of electricity is growing rapidly due to economic growth and increases in population. With the consideration of environmental issues and sustainable development in energy, renewable energy such as wind, solar, and tidal wave should be only resources to be explored in theory. But the growth in demand is also a heavy factor in energy equations so the renewable energy alone is not able to generate enough electricity to fill the gap within a short time of period. Power generation using fossil fuels is inevitable, especially, coal fired power generation is found to be an unavoidable choice due to its huge capacity and flexibility in load following ([1], [2]).

The conventional coal fired power plants have a huge environmental impact and lower energy conversion efficiencies. Any new coal fired power plants must be cleaner compared with traditional power plants. Supercritical power plants are the most suitable choice with consideration of the factors in environmental enhancement, higher energy efficiency and economic growth. However, there has been an issue to be addressed to adopt this technology in the UK because the dynamic response and performance still require study for better understanding supercritical plants in relation with conventional subcritical plants, and the supercritical units are considered by others to be unreliable in comparison with subcritical units [3]. Therefore, the characteristics of supercritical plants remain to be considered and investigated. Supercritical boilers have to be once-through type boilers because there is not distinction between water and steam phases in supercritical process so there is no need for drum to separate water steam mixture. Due to the

absence of the drum, the once-through boilers have less stored energy and faster response than the drum boiler plants. However, there are several advantages of supercritical power plants over traditional subcritical plants include:

- Reduced fuel cost due to improved plant efficiency.
- Significant improvement of environment by reduction in CO₂ emissions.
- Plant costs less than subcritical technology costs and other coal technologies.
- Can be fully integrated with appropriate CO₂ capture technology.
- Fast response due to load changes and high capacity which make them suitable for base load operation, and also for fast load demand following.

From the literature survey, it has been found that several models have been reported with emphasis on different aspects of the boiler characteristics. Studying the response and control performance of once through supercritical (SC) units began on 1958 when work was started on a simulation of the Eddystone I unit of Philadelphia Electric Company and the work was extended for simulation of Bull run SC generation unit ([4], [5]). Yutaka Suzuki *et al.* modelled a once through SC boiler in order to improve the control system of an existing plant. The model was based on nonlinear partial differential equations, and the simulation results indicated that the model is valid ([6]). Wataro Shinohara *et al.* (1996) presented a simplified state space model for SC once through boiler-turbine and designed a nonlinear controller [7]. Pressure node model description was introduced by Toshio Inoue *et al.* for power system frequency simulation studies [8]. Intelligent techniques contributions have yielded an excellent performance for modeling. Neural network has the ability to model the SC power plant with sufficiently accurate results if they are trained with suitable data provided by operating unit [9]. However, neural network performances are unsatisfactory to simulate some emergency conditions of the plant because NN method depends entirely on the data not on physical laws. Simulation of SC boilers may be achieved either theoretically based on physical laws or empirically based on experimental work. In this paper, the proposed mathematical model is based on thermodynamic principles and the model parameters are identified according to a 600MW SC power plant operating currently in China. The simulation results show that the model is trustable to simulate the whole once-through mode of operation.

II. MATHEMATICAL MODEL OF THE PLANT

A. Plant description

The unit of a once-through supercritical 600MW power plant is selected for the modelling study. The schematic view of the boiler is shown in Fig.1. Water from the feedwater heater is heated in the economizer before entering the superheating stages through the waterwall. The superheater consists of three sections which are low temperature superheater, platen superheater, and final stage superheater. The main steam outlet temperature is about 571C° at the steady state and a pressure is 25.5 MPa. There are 2 reheating sections in the boiler for reheating

the reduced thermal energy steam exhausted from the high pressure turbine. The inlet temperature of the reheater is 309 C° and the outlet temperature is nearly 571 C° and average pressure is 4.16MPa. The reheated steam is used to energize the intermediate pressure turbine. Finally, the mechanical power is generated through multi-stage turbines to provide an adequate expansion of the steam through the turbine and subsequently high thermal efficiency of the plant.

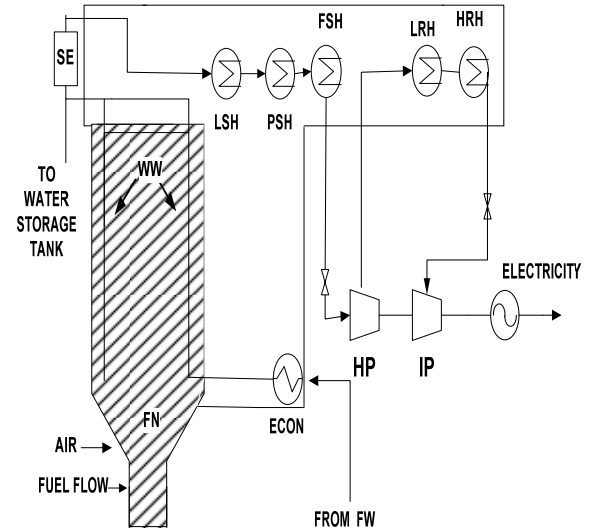


Fig.1. schematic view of the plant

B. Assumptions

Assumptions which are stated to simplify the process should be logically acceptable and sufficient to transfer the model from its complex physical state to simple mathematical state. A great attention should be taken for the choice of assumptions because some assumptions result in over-simplification and nonrealistic system. For successful mathematical modeling, the following general assumptions are made:

- Fluid properties are uniform at any cross section, and the fluid flow in the boiler tubes is one-phase flow.
- In the heat exchanger, the pipes for each heat exchanger are lumped together to form one pipe.
- Only one control volume is considered in the waterwall.
- The dynamic behaviour of the air and gas pressure is neglected.
- Only the change in internal energy is considered, the deviations or changes of kinetic energy and potential energy of fluid are neglected.

C. Heat Exchanger model

The various heat exchangers in the boiler are modelled by mass and energy balances. The sub-cooled water in the economizer is transferred directly to a supercritical steam through the waterwall without passing with the evaporation status.. The equations are converted in terms of the derivatives pressure and temperature of the heat exchanger. Refer to Appendix A for the nomenclature and abbreviations. The mass balance equation of the heat exchanger (control volume) is:

$$\frac{dm}{dt} = \dot{m}_i - \dot{m}_o \quad (1)$$

For constant effective volume, Equation (1) will be:

$$V \frac{d\rho}{dt} = \dot{m}_i - \dot{m}_o$$

The density is a differentiable function of two variables which can be the temperature and pressure inside the control volume, thus we have:

$$V \left(\frac{\partial \rho}{\partial P} \Big|_T \cdot \frac{dP}{dt} + \frac{\partial \rho}{\partial T} \Big|_P \cdot \frac{dT}{dt} \right) = \dot{m}_i - \dot{m}_o$$

The energy balance equation:

$$\frac{dU_{hx}}{dt} = \dot{Q}_{hx} + \dot{m}_i h_i - \dot{m}_o h_o$$

Also

$$\frac{dU_{hx}}{dt} = V \left[h \left(\frac{\partial \rho}{\partial P} \Big|_T \cdot \frac{dP}{dt} + \frac{\partial \rho}{\partial T} \Big|_P \cdot \frac{dT}{dt} \right) + \rho \left(\frac{\partial h}{\partial P} \Big|_T \cdot \frac{dP}{dt} + \frac{\partial h}{\partial T} \Big|_P \cdot \frac{dT}{dt} \right) \right] - V \frac{dP}{dt}$$

Then, the energy balance equation becomes:

$$V \left[h \left(\frac{\partial \rho}{\partial P} \Big|_T \cdot \frac{dP}{dt} + \frac{\partial \rho}{\partial T} \Big|_P \cdot \frac{dT}{dt} \right) + \rho \left(\frac{\partial h}{\partial P} \Big|_T \cdot \frac{dP}{dt} + \frac{\partial h}{\partial T} \Big|_P \cdot \frac{dT}{dt} \right) \right] - V \frac{dP}{dt} = \dot{Q}_{hx} + \dot{m}_i h_i - \dot{m}_o h_o \quad (2)$$

Solving (1) and (2) to get the pressure and temperature state derivatives,

$$\dot{P} = \frac{\dot{Q}_{hx} + \dot{m}_i H_i - \dot{m}_o H_o}{\tau} \quad (3)$$

$$\dot{T} = C(\dot{m}_i - \dot{m}_o) - DP \quad (4)$$

where:

$$H_i = \left(h_i - h - \frac{\rho \frac{\partial h}{\partial T} \Big|_P}{\frac{\partial \rho}{\partial T} \Big|_P} \right) \quad (5)$$

$$H_o = \left(h_o - h - \frac{\rho \frac{\partial h}{\partial T} \Big|_P}{\frac{\partial \rho}{\partial T} \Big|_T} \right) \quad (6)$$

$$\tau = V \left(\rho \frac{\partial h}{\partial P} \Big|_T - \frac{\rho \frac{\partial \rho}{\partial P} \Big|_T \frac{\partial h}{\partial T} \Big|_P}{\frac{\partial \rho}{\partial T} \Big|_P} - 1 \right) \quad (7)$$

$$C = \frac{1}{V \frac{\partial \rho}{\partial T} \Big|_P} \quad (8)$$

$$D = \frac{\frac{\partial \rho}{\partial P} \Big|_T}{\frac{\partial \rho}{\partial T} \Big|_P} \quad (9)$$

The temperature of the superheater is controlled by the attemperator. Therefore, the input mass flow rate to the superheater is the addition of the SC steam and the water spray from the attemperator. The amount of attemperator water spray is provided by opening the spray valve which

responds to a signal from PI controller. This prevents the temperature high fluctuation and ensures maximum efficiency over a wide range of operation.

D. Fluid flow

The fluid flow in boiler tubes for one-phase flow is:

$$\dot{m} = k \cdot \sqrt{\Delta P} \quad (10)$$

Which is the simplist from for fluid flow in boiler tubes. The flow out from the reheater and main steam respectively are:

$$\dot{m}_{rh} = K'_1 \cdot \frac{P_{rh}}{\sqrt{T_{rh}}} \cdot \mathfrak{N}_{rh} \quad (11)$$

$$\dot{m}_{ms} = K'_2 \cdot \frac{P_{ms}}{\sqrt{T_{ms}}} \cdot \mathfrak{N}_{ms} \quad (12)$$

The detailed derivation of (11), and (12) can be found in [10].

E. Turbine / Generator Model

The turbine and generator can be modelled only by energy balance equation. The boiler response is very slow compared with turbine/ generator responses. Therefore, there is no need to detail the model of the turbine/generator as in the case of SC boiler. The turbine energy balance equation:

$$\dot{m}_{ms} \cdot (h_{ms} - h_{out}) = \dot{W}_{hp} \quad (13)$$

$$\dot{m}_{rh} \cdot (h_{ms} - h_{out}) = \dot{W}_{ip} \quad (14)$$

The generated power of the plant:

$$MW = \varepsilon(\dot{W}_{hp} + \dot{W}_{ip}) \quad (15)$$

F. Heat transfer rate

The combustion heat transfer rate is a first order lag of the fuel flow rate ([8], [11]). The heat transfer rates of the various heat exchangers are directly proportional to the main combustion heat transfer rate. This greatly simplifies the mathematical model without sacrificing the important dynamics to be considered for the plant.

$$\dot{Q} = \frac{1}{1 + \tau_1 s} ffr \quad (16)$$

$$\dot{Q}_{ec} = K_{ec} \dot{Q} \quad (17)$$

$$\dot{Q}_{ww} = K_{ww} \dot{Q} \quad (19)$$

$$\dot{Q}_{sh} = K_{sh} \dot{Q} \quad (20)$$

$$\dot{Q}_{rh} = K_{rh} \dot{Q} \quad (21)$$

G. Final form of the model

$$\dot{x}_1 = f(x_1, \varphi, \ell) \quad (22)$$

$$\dot{x}_2 = f(x_1, \varphi, \ell) \quad (23)$$

$$y = f(x_1, x_2, \varphi, \ell) \quad (24)$$

where \dot{x}_1 represents the pressure state vector, \dot{x}_2 is the temperature state vector, φ is the input vector which contains the direct inputs of the boiler (fuel and feedwater flows), and ℓ is the intermediate variables vector which

are the intermediate mass flow rates of fluid. The output vector y can be taken as any variable from the vectors x_1 and x_2 since the model is implemented in MATLAB / SIMULINK, the observation of any variable dynamics is available at any point in the model.

III. MODEL PARAMETER IDENTIFICATION

A. Data selection:

The data should be informative for successful identification procedures. The once-through operation of the plant starts nearly above 30% of rated load (Fig.2.). The behaviour of the plant during start-up is completely different from that of the once-through mode because the separator separate the water from steam during start-up process and the water is re-circulated for further heat addition. After start-up process is completed, the circulation valve closes to allow the once-through operation. Therefore, the model for the boiler during start-up is different from the once-through mode model and the start-up data shouldn't be used for identification of the proposed model parameters. Only the data of once-through operation is used for the identification and verification

B. Identification procedures:

The parameters of the model which are defined by from (5) to (9) and the other parameters of mass flow rates' gains , heat transfer constants, turbine/generator parameters are all identified by genetic algorithm. Even though some of these parameters can be found from the properties of water/steam or steam table and thus they are inherently not constant, but these parameters are fitted directly to the actual plant response to save time and effort. Various boiler responses have been chosen for identification and verification. First, the parameters of pressure derivatives equations are identified. Secondly, the identification is extended to include the temperature equations and turbine/generator model.

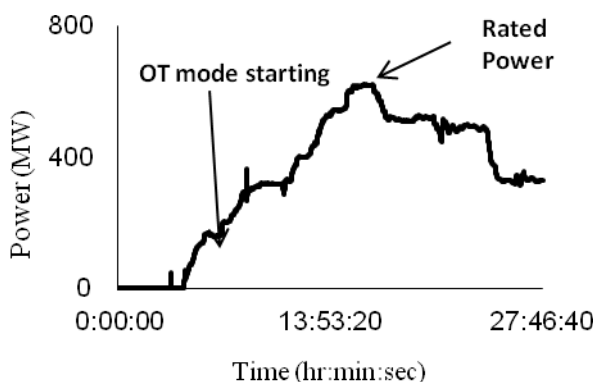


Fig.2. Power survey for the modelled 600MWSC plant Over more than 24hrs

The responses which are chosen for identification and verification are:

- Reheater pressure.
- Main SC steam pressure.
- Main SC steam temperature.
- Mass flow rate of SC steam from boiler main outlet to HP turbine.

- Mass flow rate of reheated steam from reheater outlet to the IP turbine.
- Generated power of the plant.

In recent years, Genetic Algorithms optimisation tool has been widely used for nonlinear system identification and optimization ([12], [13], [14]). This is because it has many advantages over conventional mathematical optimization techniques. It has been proved that the GA tool is a robust optimization method for parameters identification of subcritical boiler models [11] and Tube Ball mills ([15]). Initially, the GA produces a random initial population. Then, it calculates the corresponding fitness function to recopy the best coded parameter in the next generation.. The GA termination criteria depend on the value of the fitness function. If the termination criteria is not met, the GA continue to perform the three main operations which are reproduction, crossover, and mutation. More details about this technique can be found in the text of David Goldberg 1989 [16]. The fitness function for the proposed model is:

$$ff = \sum_{n=1}^N (R_m - R_{si})^2 \quad (25)$$

which is the sum of the square of the difference between measured and simulated responses for each of the variables mentioned in this section. N is the number of points of the recorded measured data, The identification scheme is shown in Fig.3. The load-up data have been used for identification from 30% to 100% of load. The next step is to verify the proposed model. The model is verified from load down from 100% to 55% and steady state data to cover the large range of once-through operation. The GA parameters for identification of optimal parameter of the model are mentioned below:

Population type:	double vector
Creation function:	uniform
Population size:	50
Mutation rate:	0.1
Mutation function:	Gaussian
Migration direction:	forward
Selection:	stochastic uniform
Crossover function:	scattered

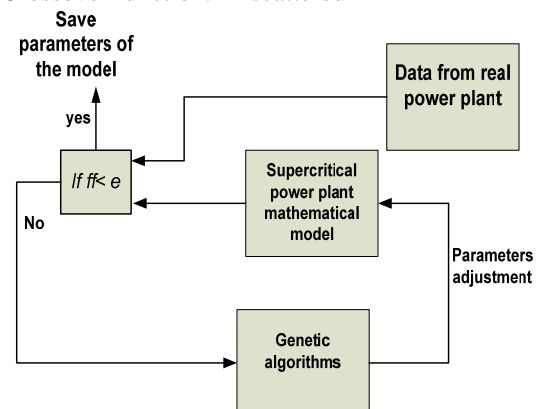


Fig.3. schematic diagram of model's parameter identification

Some of the identification results are shown in Figs.4-7, where the dashed line for the simulated and solid line for the measured time responses. From the identification results, it has been observed that the power responses are

well matched; the simulated main steam pressure and main steam temperature responses are also reasonably matched. There are so many parameters in the model so we cannot mention them all. The optimal parameters of the heat exchanger model are mentioned in Table 1 and for heat transfer rates are mentioned in Table 2.

Table 1. Heat exchanges' parameters

HX	H_i	H_o	C	D
ECON	10.2	13.6	2.1e-6	-3.93
WW	12.2	13.3	-1.2e-6	-0.1299
SH	20.5	45.9	1e-6	-3.73
RH	19.8	22.	-1e-6	-17.9

Table 2. Heat transfer rate parameters

τ_1 (s)	K_{ec}	K_{ww}	K_{sh}	K_{rh}
9.3	5.7785	7.78	23.776	21.43

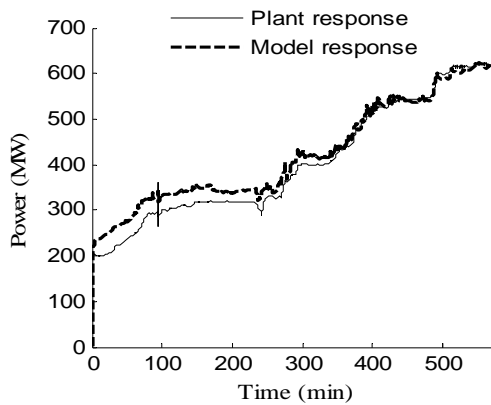


Fig.4 Power response for plant and Model

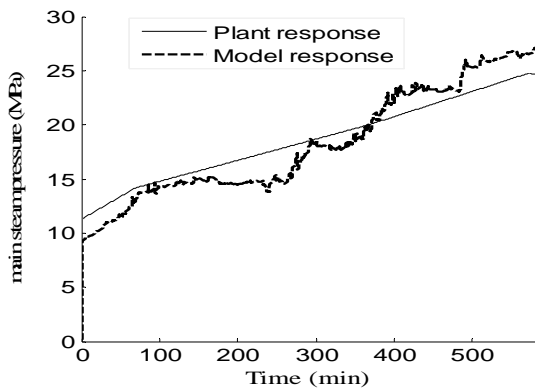


Fig.5 Load-up main steam pressure response

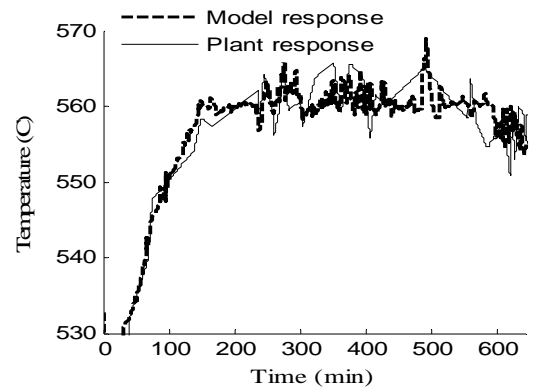


Fig.6 Load-up main steam temperature

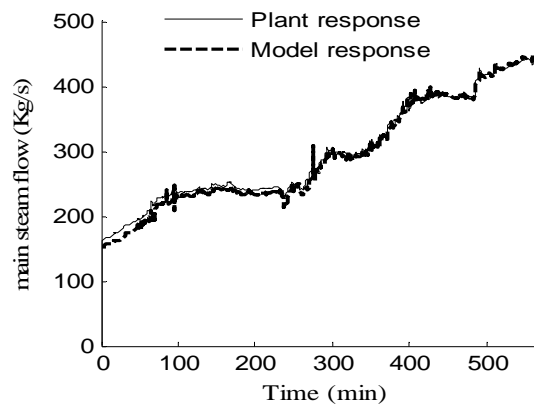


Fig.7 Load-up main steam flow

IV. MODEL VERIFICATION

The validation of the proposed model has been performed on the variables mentioned in section. III by a number of data sets which are the load down and steady state data. Figs.8, 9, and 10 demonstrate the reheater pressure and power for steady state operation. Also, the main steam flow rate and power for load down operation are shown in fig.6. From the results mentioned, it is obvious that the model response and the actual plant response are very well agreed for the power, reheater pressure and steam flow rate. Thus the model is valid for steady state and load change conditions and it will be very useful for control synthesis.

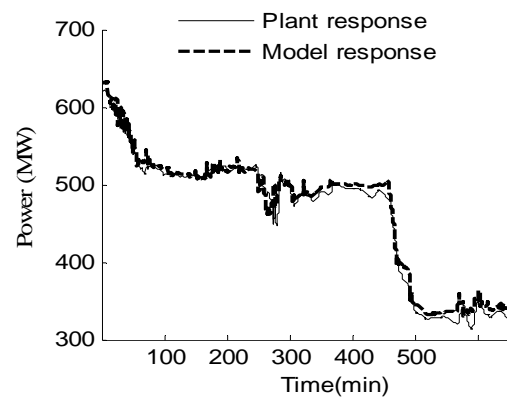


Fig.8 Load-down power response

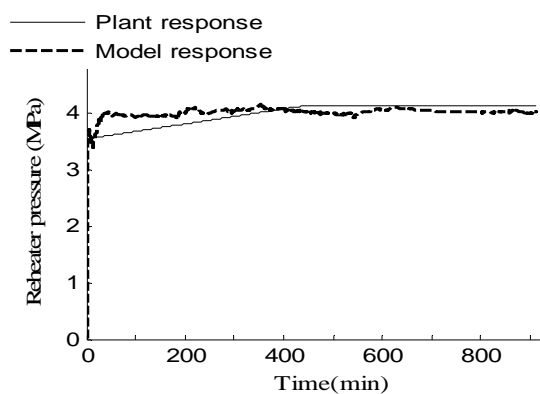


Fig.9 Steady state reheat pressure

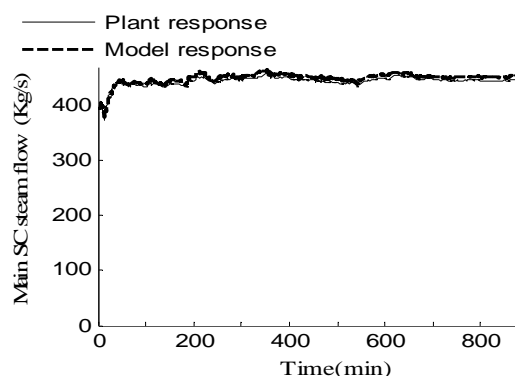


Fig.10 steady state steam flow rate

V. CONCLUDING REMARKS

A model of coal fired power generation with supercritical boiler has been presented. The model is based on thermodynamic laws and identified according to operating data record. The model is also verified by different data sets and the simulation results show that the model is valid. As a future work, the model will be combined with a nonlinear mathematical model of coal mill to obtain a wide mathematical model for the whole process from coal grinding to electricity generation. In addition, a further study will be carried out to improve the plant response by control system design.

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