# MODELING OF A COMBINED CYCLE POWER PLANT

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UNIVERSITI TEKNOLOGI MALAYSIA

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# MODELING OF A COMBINED CYCLE POWER PLANT

**FARIDAH MOHAMAD IDRIS**

A thesis submitted in fulfilment of the requirements for
the award of the Degree of Master of Engineering (Electrical)

**Faculty of Electrical Engineering**
**Universiti Teknologi Malaysia**

NOVEMBER 2001

# DECLARATION

I declare that this thesis entitled 'Modeling of A Combined Cycle Power Plant' is the result of my own research except as cited in references. This thesis has not been accepted for any degree and is not concurrently submitted in candidature of any degree.

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Date: **15 November 2001.**

# DEDICATION

And God created this universe in harmony.
And God's Greatness could only be found by those who seek.

And God is the One that taught through writings.

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# ABSTRACT

The combined cycle power plant is a non-linear, closed loop system, which consists of high-pressure (HP) superheater, HP evaporator, HP economizer, low-pressure (LP) evaporator, HP drum, HP deaerator, condenser, HP and LP steam turbines and gas turbine. The two types of turbines in the plant i.e. the gas turbine and the HP and LP steam turbines operate concurrently to generate power to the plant. The exhaust gas which originate from the combustion chamber drives the gas turbine, after which it flows into the heat recovery steam generator (HRSG) to generate superheated steam to be used in driving the HP and LP steam turbines. In this thesis, the combined cycle power plant is modeled at component level using the physical method. Assuming that there is delay in transport, except for the gas turbine system, the mass and heat balances are applied on the components of the plant to derive the governing equations of the components. These time dependent equations, which are of first order differential types, are then solved for the mass and enthalpy of the component. The solutions were simulated using Matlab Simulink using measured plant data. Where necessary there is no plant data available, approximated data were used. The generalized regression neural networks are also used to generate extra sets of simulation data for the HRSG system. Comparisons of the simulation results with its corresponding plant data showed good agreements between the two and indicated that the models developed for the components could be used to represent the combined cycle power plant under study.

# ABSTRAK

Loji penjana kuasa tergabung adalah sebuah sistem yang tertutup dan bersifat tidak linear. Ia mengandungi komponen-komponent penjana wap air lampau hangat (*superheater*) bertekanan tinggi, pengwap (*evaporator*) bertekanan tinggi, *economizer* bertekanan tinggi, pengwap bertekanan rendah, *drum* bertekanan tinggi, *deaerator* bertekanan tinggi, penyahwap (*condenser*), penjana kuasa wap air yang bertekanan tinggi dan rendah, serta penjana kuasa gas. Kedua-dua penjana di dalam loji tersebut, iaitu penjana kuasa wap air yang bertekanan tinggi dan rendah, serta penjana kuasa gas, beroperasi serentak untuk membekalkan kuasa. Penjana kuasa gas menggunakan gas hasil dari proses pembakaran untuk penjanaan kuasanya, manakala penjana kuasa wap air menggunakan wap air lampau hangat (*superheated steam*) yang dihasil oleh *heat recovery steam generator* (*HRSG*) dari sisa haba yang terdapat dalam gas pembakaran tersebut. Dalam tesis ini, loji penjana kuasa tergabung ini dimodel menggunakan kaedah Fizik pada peringkat komponennya. Dengan menganggap terdapat lambatan dalam pengangkutan jirim dalam setiap komponen loji kecuali penjana kuasa gas, maka imbangan jirim dan tenaga dikenakan terhadap komponen dalam loji tersebut. Persamaan pembeza tahap pertama, yang menghuraikan dinamik komponen kemudiannya diterbit dan diselesaikan. Penyelesaian yang diperolehi disimulasi menggunakan Matlab Simulink dan data yang diukur dari loji sebagi masukan simulasi. Di mana perlu, penghampiran dilakukan untuk menganggar data bagi masukan simulasi. Bagi sistem HRSG, data tambahan diterbit menggunakan *generalized regression neural networks*. Bandingan antara hasil simulasi dan data diukur yang diukur dari loji menunjukkan persetujuan nilai antara keduanya. Oleh itu, model-model yang dibangunkan untuk komponen-komponen bagi loji tergabung tersebut boleh digunakan sebagai simulasi penjana kuasa tergabung berkenaan.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

In a combined power plant system, the various interactions between the parameters of the plant may be modeled by applying certain physical or statistical methods on the system. For a dynamic modeling, the system properties were derived as a function of time and these properties were later simulated using a simulation tool. For a large-scale system such as the combined cycle power plant, non-linear interactions between the various variables in the system makes modeling the plant more difficult, more so when the models are time-dependent. The modeling of such system usually involves the breaking-up of the system into smaller components and modeling each components separately. Linearization of the system is usually carried out when the degree of non-linearity of the system is too high to be handled. A number of works was done on dynamic modeling of the boiler in a power plant system. Among works were from Lu , De Mello e*t.al*. (1991) and Astrom and Bell (1988). McDonald *et.al*. (1970) developed a dynamic boiler model with high degree of non-linearity, based on physical method. It has 14 first order non-linear differential equations and 82 linear and non-linear algebraic equations (Ordys, 1995).

For dynamic power plant systems, Ordys et. al. (1994) have proposed a physical model based on a hypothetical combined cycle/combined heat power plant (CC/CHP). The governing equations of the system were solved using state space method. $\text{Matrix}_x$ and Fortran subroutines were used to simulate the model. Ordys et. al. also used the model. al. to study the effect of the controller on the system.

For the purpose of this thesis, the dynamics of an unfired combined cycle power plant one of the type that is currently operating in Malaysia, were studied and modeled. The model proposed by Ordys et. al. (1994) on the hypothetical Skegton Unit, which was of the combined cycle/combined heat power plant (CCHP), was applied on the plant under study. Instead of state space method, Matlab Symbolic Math Toolbox command *dsolve* (The MathWorks Inc., 1998) was used to solve the time-dependent variables of the plant.

The solutions for the systems in the unfired combined cycle power plant were simulate using Matlab Simulink. The simulation results were compared with measured plant data to verify the validity of the model developed. However, no controller effect was simulated in this model.

The dynamic models of the plant under study include the heat recovery steam generator (HRSG), high-pressured (HP) drum, HP deaerator, condenser, HP steam turbines. For the gas turbine system, which comprised of compressor, combustion chamber and gas turbine, steady state model was used.

For the dynamic models, the mass flow dynamics between input and output are modeled as first order lag where there exist energy storage and transport delay in the system. For the gas turbine system, the energy storage and transport delay in the system are relatively small and thus steady state equations are applied instead (Ordys et. al., 1994).

As the plant under study is real power plant, obtaining sufficient data for simulations of the power plant models developed, were often difficult due to limitations of real-time data measurement locations of the plant and the to continuous nature of the plant operations. Therefore, some of the parameters in the models would have to be approximated using certain assumptions.

The simulation results from the models during steady states were compared against plant data where possible. The comparison shows good agreements between simulations at steady state for the HRSG, HP drum and HP deaerator models and its corresponding steady-state plant data. Good agreements were also seen from the comparison of steady state models of gas turbine system and its corresponding plant data.

For the dynamic model of the condenser developed, the scale-up parameters of the condenser of the Skegton Unit (Ordys *et.al.*, 1994) were used instead, due to the unavailability of plant data under study at the time. The parameters of the Skegton Unit used as simulation inputs to the condenser model, are sized to suit the condenser of the plant under study. The comparison between the simulation results of the condenser using the scale-up parameters of the condenser of the Skegton Unit and the variables of the plant under study, showed good agreements.

The comparison between simulation results of the dynamic model of the HP steam turbine and its corresponding plant data shows good agreement. However for the LP (low-pressured) steam turbine, arbitrary outlet mass flows were selected as input data to the simulation of the models developed, due to insufficiency of plant data.

As limited sets of data were available for simulation of the models developed, extra sets of data were generated for the HRSG for the plant under study, using generalized regression neural networks from the Matlab Neural Network Toolbox. Comparison of results from the simulations of HRSG using the data generated by the generalized regression neural networks and the real data plant (and approximated) from the showed that showed that generally the former were lower in value than the latter.

## 1.2 The Modeling

A programme using a mathematical model could possibly simulate the behavior of a power plant. Modeling of a plant involves the study of the plant behavior under the influence of certain parameters of the plant.

By applying certain physical laws such as the conservation law or by using statistical method, the governing equations of the plant were derived. The governing equations usually contain the relation between the dependent and independent variables of the plant.

In modeling the dynamics of the plant, the trajectories of the system variables were traced with respect to time. The dynamic simulation of a system requires the variables of the plant to be written as a function of time. In physical method, these functions were usually formed in the governing equations as derivatives of times.

The derivatives were solved for the dependent variables of the plant by using suitable technique e.g. solution using mathematical software, state space method, linear transform. Programming tool such as Matlab, has toolbox i.e. Matlab Symbolic Math Toolbox to solve differential equations. In this thesis, the line command *dsolve* (The MathWorks Inc., 1998) from toolbox Matlab Symbolic Math Toolbox was used to solve the governing equations of the power plant system under study.

For a multivariate plant, the dynamic trajectories may be influenced by a set of variables simultaneously. In a non-linear plant, the existence of one independent variable may depend upon another. The interdependency of the variables in the plant may lead to a high degree of non-linearity in the plant. In this state, the existence of one variable in a component may actually depend on existence other variables in other components of the plant. Thus, formulating the one variable as a function of other variables in the plant may lead to a very complicated governing equation and this equation may become too complex to be solved. Even if the solutions were found, it may be too unpractical to be used as tools in the design of the plant and for control purposes.

For a complex plant such as the combined cycle power plant, the non-linearity of the plant could be reduced by applying certain assumptions, e.g. inlet and outlet flow of the system were time invariant. The linearization of the plant would then make the modeling of the plant easier and more practical to be utilized at later stage.

For a large-scale system such as the combined cycle power plant, modeling the dynamics of the system properties as a whole may not be practical and too difficult to handle. The variables in the plant effect each other in complex manner - changing the properties of one component in the plant may indirectly result in changing the properties of other component as well. In this case, the plant is usually broken up into smaller components, where the modeling is then carried out on component levels.

Once the concept of the model of the plant has been established i.e. the governing equations of each of the component have been derived, a technique for solving dependent variables of the component has been identified, relevant sets of obtained, and appropriate simulation tool is then chosen.

A number of software such as Matrix$_x$, SystemBuild, Xmath and Matlab Simulink provides suitable environment for simulation (Ordys *et.al.*, 1994). For this thesis, Matlab Simulink was chosen for flexibility for numerical computations, as well as easy visualization of the concept of the model being built.

When the model of the plant has been encoded using the simulation tool, plant data is input to the model and the programme is then run. Output results from the simulation of the model should be tested against real data to validate the model.

If the model does not show good result compared to real data, appropriate adjustment of the model should then made. The additional conditions and physical laws may have to be added to the present model, and new data approximations may have to be made. The adjusted model should then be tested again against real. The process of modeling is repeated until a reasonable model is reached.

## 1.3 Objective of Modeling

Modeling of a plant is more often the alternative to real time experiments - when the plant under study is complex in nature such as the combined cycle power plant, and the real time experiments on the plant is not cost effective. The modeling and simulation of a system is more often done when the system under study is:

(i) not accessible to experimentation's, due to safety reasons
(ii) expensive and often time consuming to conduct real time experimentation's
(iii) real time data measurement cannot be done due to limitation of sensors or the unavailability of measurement locations
(iv) to provide information on the mechanism of the system for tuning and optimizing purposes

Simulating the power plant will give a tool to manipulate the plant system and observe the consequences without actually having to carry out the actions on the plant itself, and thus avoiding damaging, endangering or halting the plant operation itself

The modeling of a plant is preferable than actual experiments, as the simulations of the conditions of the operating system are often carried out in a laboratory under manageable situations. With a given set of input data, the system simulated could be run inside a laboratory to observe the effect of varying different parameters of the plant, without actually running the plant itself.

Besides saving a lot of valuable time, simulation of a plant would more often than not, be more cost effective than actually carrying out the experiments on the plant itself. Actual experiments involve trials and errors, and even detailed planning of the experiment to ensure the success of the experiments, as well as to avoid any untoward consequences.

For the system such as the power plant, adequate data sampling of the plant may not easily be carried out due to limitation of sensor locations in the plant. The plant was not designed to accommodate experiments and continuos operation of the plant does not permit for interruptions. Running a simulation with arbitrary value may solve this kind of problem.

The modeling of the plant may give an insight into the plant structure and mechanism. It also provides simulation tool to optimize the plant operation where adjusting the input signals in simulated environment to optimize the parameters concerned is easier done than on-line parameter optimization. It may also make the design of similar system in future less time consuming.

With the modeling of a dynamic system, the system could be simulated from start-up to steady state operation. The simulation time could further be extended to observe the behavior of the system during steady state operation, when the system reaches stability as time goes towards infinity. In this case the simulation time is extended until all transient values fall to zero - at this instant of time when output from the model stabilizes, the system is then in steady state condition.

For these reasons, simulation a system by adopting certain models may prove to be an advantage, even though initially it requires a lot of study to understand the mechanism of the system. While modeling of a system requires the understanding of the system which could be tedious at times, the results is more than worth the effort.

In this thesis, a real combined cycle power plant is used as study case for modeling the dynamic properties of a plant. Using physical method, the dynamics of the combined power plant is modeled to gain insight into the mechanism of the plant. Through the modeling of the plant, the methodology for modeling a dynamic system especially for a combined cycle power plant, approximations used in estimating certain parameters the plant for simulation inputs and validation of the models developed for the plant shall be established. The same process used in modeling the combined cycle power plant could also be applied for dynamic of modeling of other systems.

The dynamic models developed for the combined cycle power plant could be used for the used for the following purposes (Lu):

(i) Operational studies to increase unit efficiency and improve operating procedure
(ii) Operational transient analysis to improve plant responses and diagnose plant faults
(iii) Control system design, analysis and test
(iv) On-line model-based operation and surveillance of plant responses.

The models developed in this thesis could be used as a platform to develop process library of the combined cycle power plant with similar configuration. Through the models developed in this thesis, the parameters of the combined cycle power plant could be then manipulated to optimize the plant operating conditions. For example, the inlet steam flow into the HP and LP steam turbine could be optimized by adjusting the parameters of the HP drum and the gas turbine which control the dynamic properties of the steam in the HP superheater. This optimization will lead to the increase in the efficiency of the plant electric generators, especially the HP and LP steam turbine, as well as the overall efficiency of the plant.

Due to time constraint and space of this thesis, the combined cycle power plant models developed in this thesis were only tested and validated against real plant data at various plant load - their dynamic behavior are observed and recorded. These observations are given numerical and graphical forms in Chapter 4 of the thesis.

The optimization of the plant under study and the variation of the plant parameters for the purpose of configuring different plant design from the one that is currently under study is not carried out due the unavailability of the operating specification of the plant, its safety operating limits and the rigorous nature of the designing and optimizing processes themselves which is beyond the scope of this thesis.

It is hoped that the models developed in this shall be used to further develop the understanding of the combined cycle power plant mechanism as a whole, and to provide tools for industrial and academic purposes.

## 1.4 Physical and Statistical Methods of Modeling the Plant

In modeling a system; mathematical formulation plays an important role in determining the structural formation of the model. The formulation should encapsulate the mechanism and characteristic properties of the system in its structure. Choosing the type of modeling suited best depends on the availability of data on the system.

Generally, there are two approaches in modeling a system, namely the statistical or the theoretical approach. While the statistical method involves the gathering of sufficient data and the analysis variance to find the correlation of the variables within the system, it does not necessarily require an in-depth understanding of the system.

On the contrary, the theoretical or physical method involves the theoretical understanding of the system. The correlation of variables in the system were based on certain universal law or hypothesis e.g. conservation principal and Newton's law. The governing equations of the system were then correlated based on these hypothesis and/or laws.

Modeling using statistical method usually involved the study of the output variation of a system with respect to its inputs. To get the readings needed for trend analysis of data; usually the signals from the inputs and outputs of the system were tapped from certain measurement points in the system. In some cases, experiments regarding to the model to be developed were carried out.

During trend analysis, the data gathered from the inputs and the outputs of the system were studied for their correlations with each other. In multivariate analysis, the continuous functional relationships among several variables were regressed.

The effects of several variables in the system were considered at once - multicollinearity, which exists between the independent variables in the system, may indicate that the system under study can be non-linear in nature.

Multiple regression models could give more insight into underlying structural relationships between the variables in the system (Glints et. al.). The model cement plant with rotary kiln done by Abu Bakar (1992) shows the effect of a multivariable system which linear in nature.

In power plant system, the block box modeling was used to model the boiler. Ordys et. al. (1995) has outlined two methods for system identification or experimental method, namely the linear method and non-linear method.

While linear method produces accurate results with block box modeling, Ordys et. al. (1995) reported that non-linear identification using the block box modeling results in complicated models in the form of large simulations codes. These codes which were based on finite element approximations to partial differential equations, were of little interest for control design due to their complexity.

In theoretical modeling, physical laws such as the energy and mass conservation principle are applied on the system under study, and certain approximations regarding the behavior of system are made. The formulation of the model for the system usually involves rigorous mathematical derivations and analysis, which at times could become complex if the system under study has a large number of parameters.

While the theoretical modeling may require detailed understanding of the system under study, the results from the simulation of the model may be more reliable than the statistical method, if adequate approximation of the system properties were made.

Physical modeling of a system normally involves the derivations of a set of partial differential equations described the behavior of the properties of the system under study. The governing equations were then solved, not necessarily simultaneously, for the solutions of the system.

In deriving the governing equations of a system, the mass and energy balances were applied on the system. Through this application, differential equations with respect to time, which describe the dynamic properties of the system were obtained and thus solved.

In power plant system, the physical modeling of the boiler was done on two level, namely the high order and the low order model, (Ordys et. al., 1995). In high order model, Mac Donald et. al. (1970) have developed a detailed boiler model by applying the mass and energy balance on the boiler-turbine system which as partitioned into 16 subsections. The model, which was non-linear, coupled and complex, has 14 first order non-linear differential equations and 82 linear and non-linear algebraic equations with 6 inputs and 6 outputs.

Several high order models of the boiler were used in the investigation the boiler control. Ordys et. al. (1995) has reported the used of high order model to design robust multivariable controller for the boiler control-oriented mathematical boiler model. Dieck-Assad and Masada (1987) have used a 32nd the boiler turbine model to solve optimal set-point scheduling problem.

Astrom et. al. (1988) reported a third order model which exhibit a complex behavior and difficult to perform linearization and analysis for controller design (Ordys et. al., 1995). In low order boiler models, Astrom et. al also proposed the first order based on global energy balance for the total plant, which consist of a single state, namely the drum pressure of the drum.

In modeling the dynamic properties of the boiler, Lu (1991) used physical technique to derive the governing equation of the boiler of a typical 660MW coal and gas fired power plant, where the responses of the boiler to typical plant disturbances were studied.

In this model, a single-phase steam volume of the boiler was modeled by applying mass and energy conservation principle on the boiler. Assuming that the volume of the boiler was constant, the mass balance on the boiler was carried out.

The rate of mass retained in the boiler was then given by the input flow minus the output flow. Using the chain rule, Lu expanded the density derivative term in the mass balance equation into partial derivatives in term pressure and enthalpy.

To derive the second governing equation of the boiler, Lu applied the energy conservation principle on the boiler. The rate of internal energy term in the equation was expended into pressure and enthalpy derivatives.

Combining both the mass and energy conversion equations, the differential equations of pressure and enthalpy with respect to time were arrived at. The dynamics of pressure and enthalpy of the boiler were simulated using programming tool Matlab Simulink.

The simulation results of responses to typical plant disturbances i.e. dynamic responses to main pressure set point (2Mpa) and main steam valve open 20%, using the data from a typical 660MW coal and gas fired power, were reported to be satisfactory.

de Mello et. al. (1991) developed a simplified drum-type boiler model to demonstrate the saturation characteristics of water/steam in the superheater, as the dominant energy storage contributors.

The storage constant, which is defined as the change in mass of the steam stored in water-walls, drum and super-heater, was studied at constant temperature. In this case, the effects were limited to pressure/flow of the boiler only.

The mass, energy and volume balance were used to derived equation for pressure rate in the boiler. Instead of using the internal energy of the gas in the boiler, de Mello et. al. used the enthalpies of liquid and gas in the boiler in the energy balance.

The density rate term in the heat balance was expanded into partial derivatives of density with respect to pressure and partial derivative of pressure with respect to time. The former partial derivative would be used to describe the storage constant, while the former would be used to describe small perturbation to the storage constant.

The terms for partial derivative of the steam densities and enthalpies with respect to pressure were evaluated from steam tables and substituted into the heat balance equation of the boiler, to solve for pressure derivative of the superheater with respect to time.

Through the model, the contribution of the storage constant was found to be proportional to the partial density of the drum with respect to pressure multiplied by the superheater section's volume, at an average constant temperature in the section.

The storage constant then was determined through solving for the rate of change of pressure for a given change in the flow out of the boiler. Thus, the storage constant for a boiler could be calculated.

Ordys et. al. (1994) developed a dynamic model of a combined cycle/combined heat and power (CC/CHP) generation plant, based on a hypothetical plant called the

Skegton Unit, which has total power output of 90MW. The configuration of the hypothetical plant was devised to illustrate the wide variety of control problem, which might arise in CC/CHP plant.

The components of the plant include two units each of gas turbines, boilers, triple stage steam turbines, condensers and feedwater system, gas damper, and valves for steam admission, throttle and high-pressured steam extraction.

As Lu and de Mello et. al., Ordys et. al. (1994) also applied the mass and energy balances on each of the system in the hypothetical (CC/CHP) plant. Through the energy and mass balances, a set of equation describing the properties of the system with respect to time were derived. These equations were solved simultaneously using the state space method.

In state space method, a set of equations, which contain derivatives of dependent variables with respect to time, which described the properties of the system, is solved simultaneously. The number of number of dependent variable to be solved should be equal to the number of the unknown variables in each of the equation.

The solutions obtained for each of the system in the plant described the behavior of the system properties with respect to time. Ordys et. al. (1994) derived the equations, which contained the derivative of dependent variables with respect to time, for each of the system under study in the plant. For each of the system, a set of time dependent equations was obtained by applying the mass and energy balance on the system.

For the state space method to be successful, the set of equations should be selected so that the number of dependent variables in the system i.e. the properties of the system, equals to the number of the unknown independent variables in the equation.

Having arrived at the sets of equations, which contained the derivatives of the dependent variables with respect to time i.e., the dynamic properties of the system, the equations were simulated using programming tool $\text{Matix}_x$ and Fortran subroutines.

The solutions from the state space method gave the trajectories of the properties the system such as the dynamic density of steam/liquid and the dynamics of heat in the system. These trajectories were fed back into the controller of the system where the inputs were adjusted so that the outputs will correspond to the set points given by the supervisory control of the system.

For the fictitious Skegton Unit, the state space method was implemented on the heat recovery steam generator (HRSG), the deaerator, feedwater system, the condenser, while the gas and steam turbines (high, intermediate and low-pressured steam turbines) were modeled in the steady state mode.

In this thesis, an real unfired combined cycle power plant was modeled using similar method as proposed as by Ordys et. al. (1994) in terms of mass and energy balance, but using different technique in finding the solution for governing equation of the Skegton Unit.

Using the configuration of this real unfired combined cycle power plant, the mass and heat balance were applied on each of the system in the plant i.e. heat recovery steam generator (HRSG), high-pressured drum, high-pressured deaerator, condenser, high-pressured and low-pressured steam turbines, gas turbine.

Except for gas turbine system, the governing equation which described the dynamic properties of each of the system in the were derived. For gas turbine, the steady state model proposed by Ordys et. al. (1994) was used.

Using the governing equations of mass and heat balance of the plant, the dynamic properties i.e. density/mass and enthalpy the steam and liquid, of the each of the system in the plant were solved using line command *dsolve* from Matlab toolbox Symbolic Math Toolbox (The Math Works, 1998).

The line command *dsolve* accepts symbolic equations representing ordinary differential equations and initial conditions, and returned the solutions. The solutions were then programmed using simulation tool Matlab Simulink (The Math Works, 1999) to observe the properties of the system against time, using real plant data.

The advantage of using direct solutions of the governing equations to simulate the model is that programming is not constrained by a set of equation, as in state space solutions. This is useful in real-time plant where some of the data could not be directly obtained but have to be calculated through another physical formulation or approximations.

Hence, some of the formulation and the approximation used could be programmed directly into the model instead of calculating or approximating the concerned parameters manually, resulting a simple-to-use programme.

To verify the model, the simulation results from the unfired combined cycle power plant model were compared against the its real plant data. For the model to be valid, the simulation results and its corresponding real plant value should not deviate too much.

## 1.5 Building the Model of a Plant

Generally, the first step in modeling a system involved the identification of the process concerned and the identification of its parameters. The parameters in the process were correlated either using probabilistic/regression or physical method

The building of a model generally involve the following steps:

(i) identification of the processes to be modeled
(ii) identification of the parameters involved in the of the processes
(iii) identification of the dependent and independent variables involved

(iv) identification of feasible method of correlating the parameters
(v) linearization of the dependent variables, if any
(vi) correlation of the variables in the system
(vii) solving the dependent variables for each process
(viii) simulate the variable with a simulation tool
(ix) verify model with real data

In building the model for a complex system such as the power plant, the more convenient way of modeling is to break the system up into smaller subsystem which is a process of its own. By breaking the system up, the fewer parameters would have to be considered when analyzing the model for the subsystem.

For a complex system such as the combined cycle power plant where numerous parameters interact with other in closed-loop system, considering the interactions of all the parameters involves at once will make the model to be build more complex and may not be feasible to be modeled.

For each of the subsystem or the component in the plant above, careful consideration should be given - from both theory and experience - about the system under study to select the potentially important variable for study (Glintz et al., 1990).

This is especially significant if block box model is to be employed in modeling the system, to eliminate the effect of redundant variables in the early stage of modeling. Having listing out the parameters of the system, the variables of the system could be determined through statistical analysis of the data.

Statistical method such as the least squares regression uses multivariate analysis to detect and correlate the dependent and independent variables of the system, and finally to regress the equation that best fit the data.

In physical model, the parameters involve in the governing equations of the system depends of the objective criteria that was initially set out in deriving the governing equations of the system, and the physical laws that have been used in deriving equations.

Conventionally, the heat and mass balances are used to derive the governing equations of a system where the mass flow and heat of the system could be obtained through empirical or theoretical means. The dependent variables, which appear in the governing equations, were solved. The parameter values, which appear in the solutions, were either obtained directly or indirectly, through measurements or calculation, depending on the availability of direct data measurement.

In this thesis, the combined cycle power plant system was broken up into six subsystems. These subsystems were the heat recovery steam generator (HRSG) which comprised of high-pressured (HP) superheater, high-pressured (HP) evaporator, high-pressured (HP) economizer and low-pressured (LP) evaporator; the high-pressured (HP) drum; the high-pressured (HP) deaerator; the condenser; the high-pressured (HP) and low-pressured (LP) steam turbines and the gas turbine.

The governing equation of steam enthalpy inside the HP superheater was derived to study the effect of varying the heat of the incoming gas to the superheater, as well as the steam flowing in from the adjacent HP drum, on the enthalpy.

As a result of applying heat balance on the exhaust gas flowing through the HP superheater, the steam flowing across the HP superheater as well as on the metal tubes of the HP superheater, the solution of steam enthalpy in HP superheater could be written as a function of properties of exhaust gas, the steam flow from the HP drum, as well as the metal tubes.

As the mass flow of exhaust from gas turbine and steam from HP drum itself were derivative of time, solving the dynamic enthalpy of steam in HP superheater in terms of these mass flow which vary with time would be complex.

Therefore, a few assumptions would have to be made to reduce the complexity of the solution and thus the non-linearity aspect of the solution. For these reasons, the inlet mass flow as the outlet mass flow of the exhaust gas and the steam to/from the superheater were assumed to be constant. Only the enthalpy of steam inside the system would changed with respect to time.

For the HP superheater of the HRSG in the combined cycle power plant under study, the enthalpy of the steam in the HP superheater was solved using the heat and mass balances mentioned. The solution for enthalpy also includes the parameters of HP superheater such as its heat capacity, volume, heat transfer coefficients from exhaust gas to metal tubes and metal tubes to steam in HP superheater, the metal tubes temperature, the steam flow and density in HP superheater, as well as the inlet and outlet steam flow. The solution also includes the properties of exhaust gas across the HP superheater i.e. its mass flow temperature.

Having arrived at the solution, a simulation tool is required to simulate the dynamics of steam enthalpy in HP superheater, which has been modeled with the physical method. The simulation tool used would depend on the computations required by the model, the user-friendly format of the tool as well as its graphical presentation capacity.

In this case, Matlab Simulink was chosen. Its icon-like functions could just be dragged and dropped into any worksheet and linkage between the functions could be easily build by drawing lines between the functions makes it easier to used than conventional line by line programming. Besides being able compile its code using other compilers such as C and Visual C++, it also has various toolboxes such as the control toolbox, digital signal processing and optimization, so that the current model could be easily upgraded later on.

The simulation of the steam enthalpy in HP superheater using Matlab Simulink requires input data. For this thesis, the real data of the HP superheater were taken from an unfired combined cycle power plant, which was operating in the country. Some of the input values of the model were not directly measured but approximated through certain assumptions (see Chapter 3 of this thesis), due to limitation of data measurement facilities at the plant.

The dynamics of steam enthalpy in the HP superheater was simulated using different sets of data. The comparisons were done between simulation output from the model during steady state condition and its corresponding values from the real plant data. The steady state conditions from the simulation of the models were obtained by extending the simulation time until all transient values fall to zero. At this state, the simulation results were recorded and compared against its corresponding real plant data.

Good agreements between simulation results and real plant data would have to be reach to verify the validity of the model developed. For physical model, the agreement between simulated values and measured data may depend on the physical laws applied during the building stage of the model, while statistical value may need more data samples and better analysis of variance technique.

In other system of the plant i.e. the HP drum, HP deaerator, condenser, HP and LP steam turbines, similar methodology as applied on the HP superheater, have been used to built the model for each component respectively. In the gas turbine, the steady state approach has been adopted, based on the model developed by Ordys et.al. (1994).

## 1.6 Data for Simulation of the Plant Models

Simulating the models of a real combined cycle plant involved the input of real-time plant data into the models being simulated, and running the models with a simulation tool, such as the Matlab Simulink. The output from the models are then compared against real-time data to see whether the outputs from the model really represent the output from the plant, under the similar conditions.

Simulating the models of a real power plant, with sufficient real-time data is important to test the reliability of the models developed and to see whether the models need further modification and adjustment, to suit to real time plant output better. Comparison of simulation results with the real-time plant data should give good agreements for the models to be accepted as representing the combined cycle power plant under study.

In real plant system such as the combined cycle power plant under study, obtaining sufficient data to simulate the models developed are limited by the measurement points of the plant, the continuous operation of the plant itself, and as well the automatic controlling system of the plant.

The data needed to simulate the models of the combined cycle power plant, which has been developed, could be categorized into two i.e. the direct real-time plant and the constants used in calculating the plant properties. Real-time plant data which were obtained directly through measurement includes the inlet and outlet mass flows into/out of the components in the plant, while the constants calculated/approximated include the enthalpy of mass flowing into/out of the components in the plant, the heat transfer coefficients of heat exchangers of the HRSG and specific heat capacity of air and exhaust gas.

For the combined cycle power plant under study, the inlet and outlet mass flows into/out of the components of the power plant were obtained indirectly through approximations. These approximations are given in Chapter 3 of the thesis. Due to limitation of sensor location in the plant under study, only the temperature and pressure and the flow of the mass inside the component of the plant were measured at various plant loads. Using approximations as described in Chapter 3, the inlet and outlet temperature values were used to approximate the inlet and outlet mass flow into/out of the components. These values of mass flow in/out of the system were used as simulation inputs to the models developed for the combined cycle power plant under study.

As the enthalpies of inlet and outlet mass flows depend on its temperature, the enthalpies could then be approximated by curve-fit polynomials of steam tables. For the heat transfer coefficients of heat exchangers of the HRSG, the calculations involved the approximations of heat being transferred from exhaust gas to the metal tubes in the heat exchangers and the steam/water inside it.

Using Matlab Simulink as simulation tool has certain advantages as it allows certain approximations to be directly programmed into its subsystem blocks, thus making the approximations easier for the user. The interpolation of curve-fit polynomials for steam enthalpies and densities, as well a the specific heat capacities of exhaust gas and air could be directly programmed into the subsystem blocks in the models simulated, using certain functions available in Matlab Simulink.

The accuracy of the approximations depends on the initial values measured from the plant and sensor locations in the plant. Certain assumptions regarding the properties of the plant would also influence the accuracy of the approximations. The ideal gas assumptions applied on the steam, exhaust gas and the air inside the plant might give good approximations for high-pressured gases but might give poor approximations for low-pressured steam in the condenser and the LP evaporator in the HRSG system.

In preparing the input data for simulations of the models for a real system such as the combined cycle power plant under study, calculations to approximate the various parameters involved in the modeling could not be avoided. Thus, the data used may not exactly represent the real-time plant data, and could only be used for steady state calculation only.

As the power plant under study operates continuously, based on the percent plant load demand from its controller, sufficient real-time parameter variations might not be obtained. As the plant operated based on its controller demand, the parameters value measured may be restricted at certain plant loads only.

Thus neural networks are used to generate extra sets of input data for simulation purposes. Using the sets of data prepared for the simulations of the HRSG of the combined cycle power under study, the generalized regression neural networks were used to generate more sets of simulation data of the HRSG.

## 1.7 The Combined Cycle Power Plant

In a large-scale system such as the combined cycle power plant, the interaction of various parameters in the plant are very complex. Understanding the mechanism of these parameters at macroscopic and microscopic levels would give an insight to plant operations and provide information on plant itself. More so, when the information gained could be useful in optimizing the plant.

The assessment of the combined cycle power plant interactions is very tedious due to enormous number parameters involved. The breaking up of the plant into smaller subsystems make the study on microscopic level much easier - the identification of parameters based on subsystems scale and the subsequent correlation between its inputs and outputs make isolation of a particular subsystem for thorough understudy much easier.

In a power generation plant, electricity is produced by the turbine system of the plant through a number of ways. In a gas-fired plant, the combustion gas is used to drive the turbine while in steam generation plant, the superheated steam is used to drive the turbine.

In combined cycle power plant, both type of turbines i.e. the steam and gas turbines, are installed in the same plant to increase the overall efficiency of the plant. Boissenin and Castanier (Ordys *et.al.*, 1995) reported that the transformation of fuel energy into electricity energy could increase over 50%, compared with traditional steam turbine plants 40% and gas turbine plant 35%.

In a combined cycle power plant, the heat recovery steam generator (HRSG) in plant extracts waste heat from the exhaust gas of gas turbine, to generate superheated steam which is then used to drive the steam turbines.

In some combined cycle power plant, additional firing is used to supply heat and to increase temperature of exhaust gas flowing to the HRSG, and thus increasing the amount of steam being produced by the HRSG. The additional firing is provided by a furnace situated near the HRSG. The flexibility of using the additional firing is a different kind of fuel could be used in the furnace.

The combined cycle power plant with supplementary fired HRSG is often referred to as the combined heat and power (CHP) plant or cogeneration plant, while the combined cycle power plant with unfired HRSG classed as standard combined cycle power plant (Ordys et.al., 1994)

**Figure 1.1** gives the configuration of a combined cycle power plant with unfired HRSG, with **Figure 1.2** shows the simplified scale-up diagram of its unfired HRSG system. **Figure 1.1** also gives the schematic diagram of mass flow throughout the combined cycle plant. This type of plant configuration is one of which is currently operating in Malaysia, and will be used as a study case in this thesis.

**Figure 1.3** shows the configuration of a combined cycle /heat power (CC/CHP) plant with a fired HRSG, with **Figure 1.4** showing the scale-up diagram of its fired HRSG. The plant in **Figure 1.3** called Skegton Unit, was used by Ordys et.al. (1994) as their case study for modeling and simulation of a power plant.

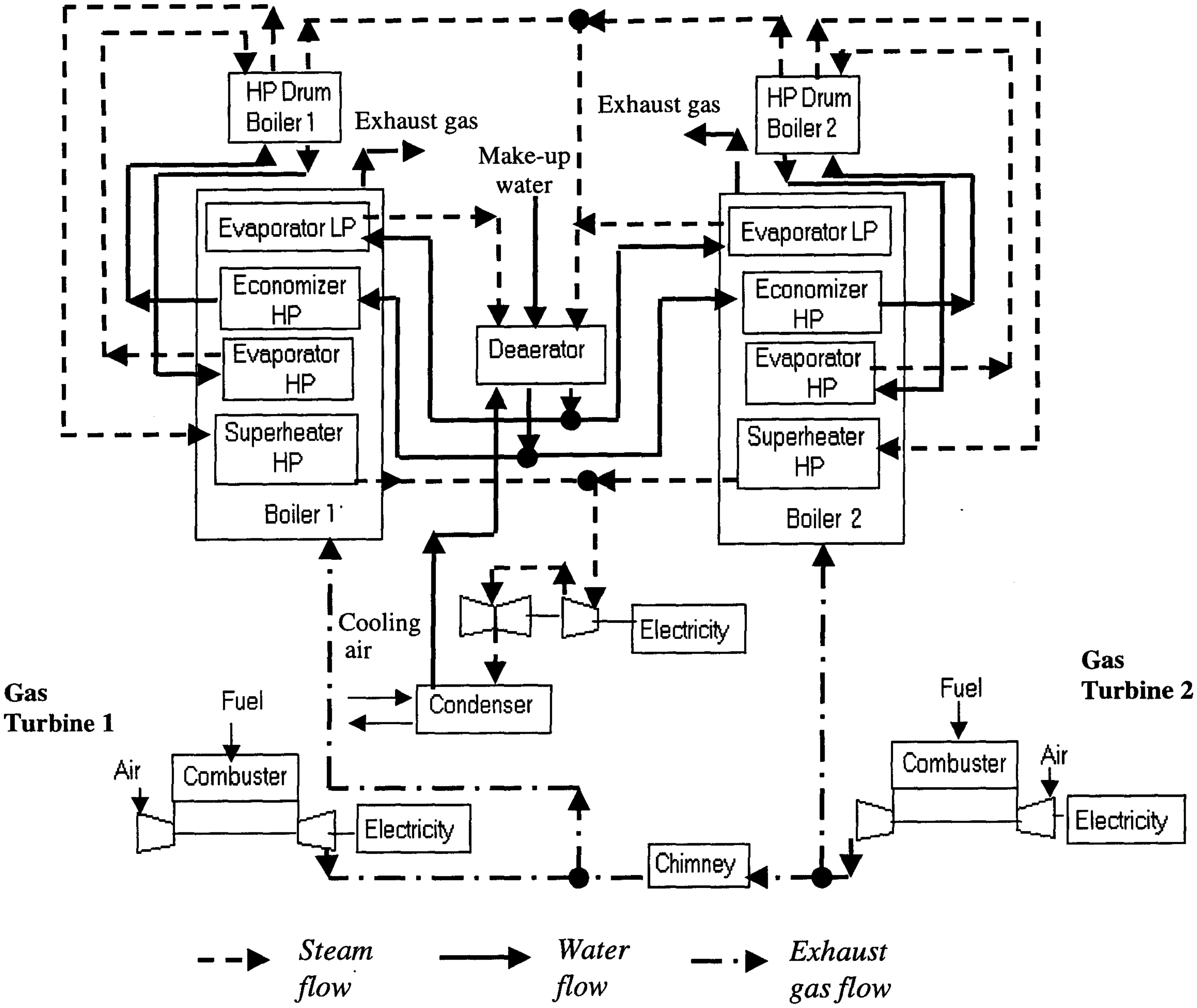

Figure 1.1 Schematic diagram of mass flow of an unfired combined cycle power pant

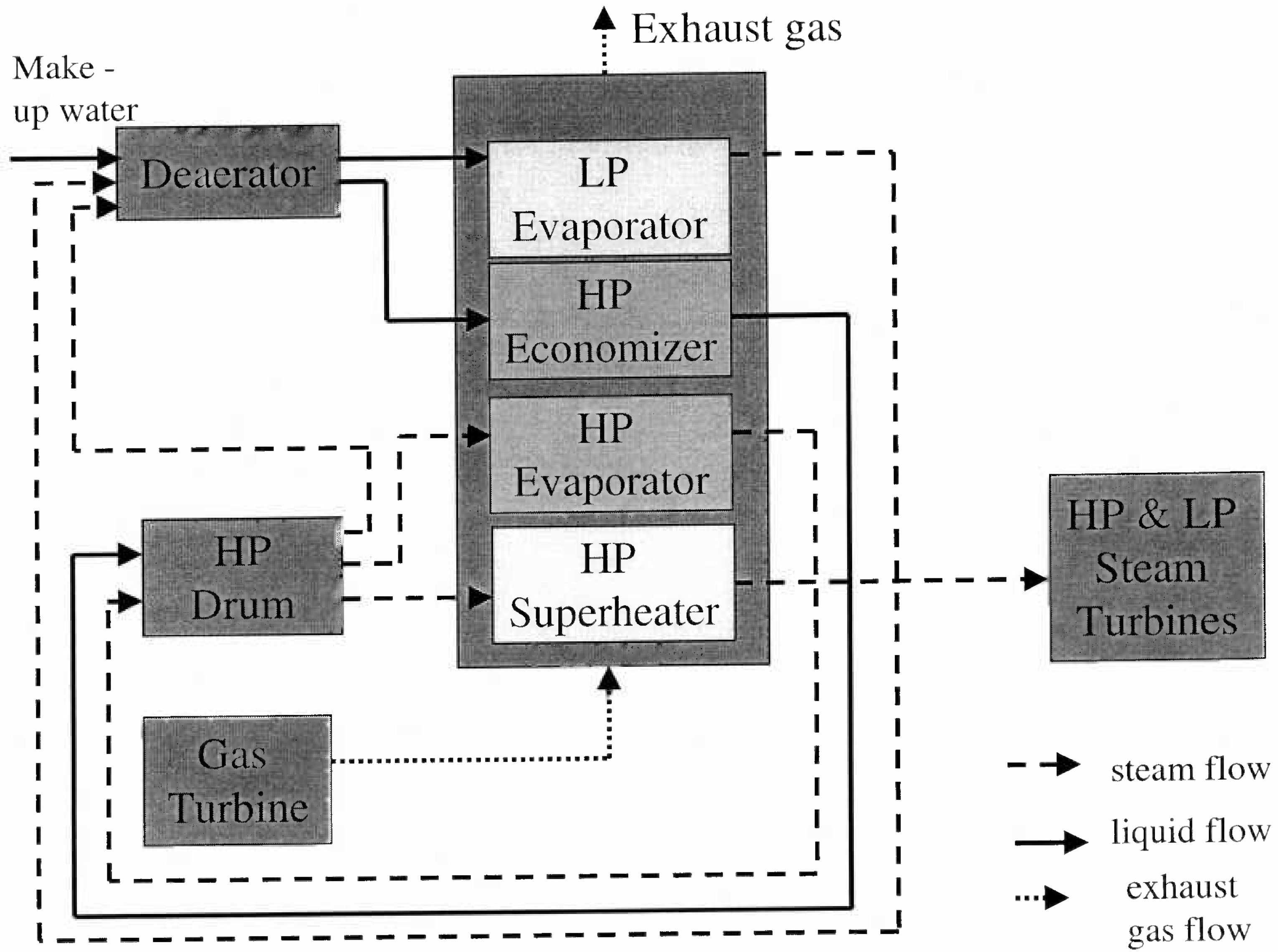

Figure 1.2 A Single Unit of Heat Recovery Steam Generator (HRSG) of Combined Cycle Power Plant

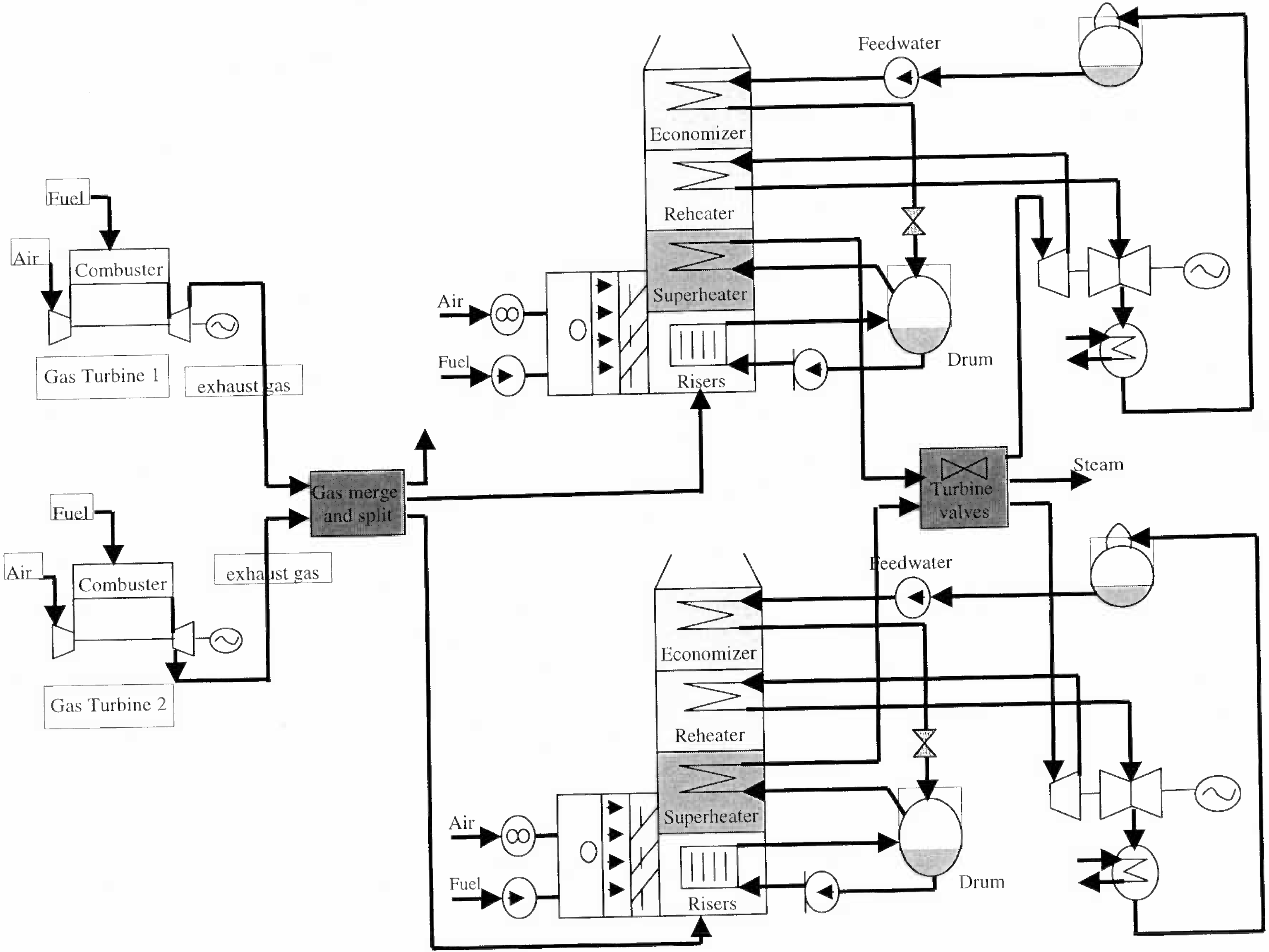

Figure 1.3 Configuration of combined cycle/heat power (CCHP) plant of Skegton Unit (Ordys *et. al.*)

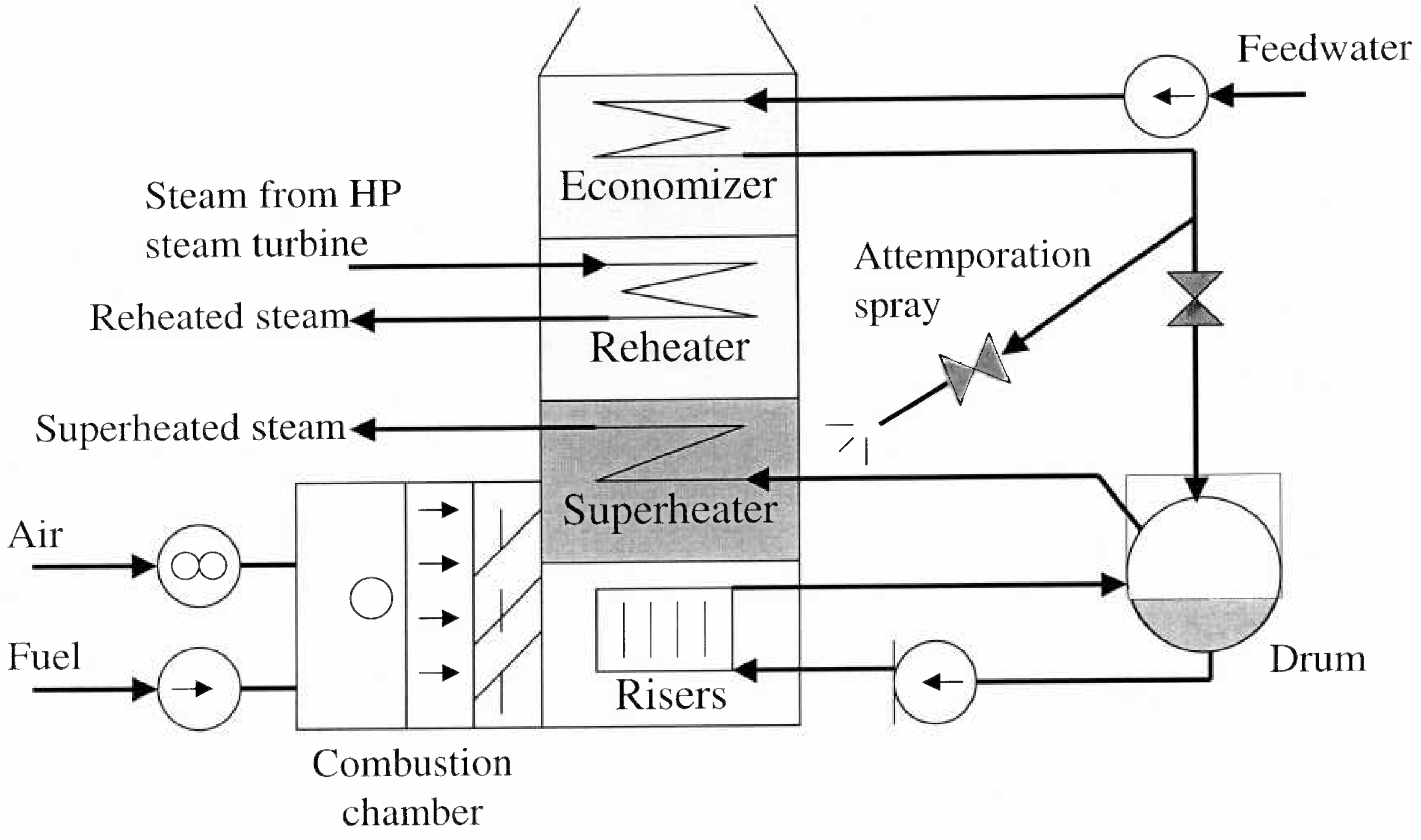

Figure 1.4 Schematic diagram of boiler in Skegton Unit (Ordys *et. al.* )

The Skegton Unit, which is fictitious, was used to illustrate the wide variety of control problems, which may arise in CC/CHP power plants. In this type of power plant, the exhaust gas from the two gas turbine was merged before being split to two separate HRSG. The HRSG of Skegton Unit consists of a riser, a superheater, a reheater and an economizer.

The exhaust gas, which entered the HRSG through the riser, was heated by the furnace before flowing into the superheater. In the superheater, the steam from the drum in Skegton unit, flowed into the superheater and absorbed heat from the exhaust gas via metal tubes of the superheater and on becoming superheated, flowed into the HP steam turbine to generate electricity.

The hot steam leaving the HP steam turbine, flows into the reheater in the HRSG to be reheated, before entering the LP steam turbine. On exiting the steam turbine, the steam enters the condenser to be cooled down to liquid phase by liquid coolant. The condensate then flows into the drum to be recycled into the economizer in the HRSG, before entering the drum.

In **Figure 1.1**, the configuration of the unfired combine cycle power plant under study in this thesis, consists of gas turbine systems, heat recovery steam generators (HRSG), drums, a deaerator, steam turbines and a condenser. **Table 1** gives the breakup of the unfired combined cycle power plant under study, and the function(s) for each the subsystem in the plant, while **Table 2** gives the components of the combined cycle/heat power (CCHP) plant of Skegton Unit.

For modeling purposes, the plant in under study in **Figure 1.2** was broken into the six components or subsystems, as given in **Table 1**, with each having their own process. These six processes if link-up together will form a whole combined cycle power plant, as in **Figure 1.2.** The followings are major processes, which occur, in the unfired combined cycle power plant under study:

**Table 1. The components of the unfired combined cycle power plant under study**

| *No* | *Component* | *No. of units* | *Functions* |
|---|---|---|---|
| 1. | Gas turbine system: | 2 | To supply exhaust gas for electricity generation and boilers in HRSG: |
| | a. compressor | 2 | a. supply of compressed air to combuster |
| | b. combustion chamber | 2 | b. fuel combustion for hot exhaust gas |
| | c. gas turbine | 2 | c. electricity generation |
| 2. | HRSG: | 2 | To generate superheated steam and recover energy from exhaust gas: |
| | a. HP superheater | 2 | a. generate superheated steam |
| | b. HP evaporator | 2 | b. generate high pressure steam |
| | c. HP economizer | 2 | c. transfer heat from exhaust gas to water |
| | d. LP evaporator | 2 | d. transfer heat from exhaust gas to low pressure steam |
| 3. | High pressure drum | 2 | Provide high pressure steam to high pressure superheater and high pressure evaporator |
| 4. | High pressure deaerator | 1 | a. Dearest feedwater from volatile gas<br>b. Provide feedwater to high pressure economizers and low pressure evaporators |
| 5. | Steam turbines: | | Convert steam thermal energy into electricity: |
| | a. High pressure steam turbine | 1 | a. Convert superheated steam thermal energy into electricity |
| | b. Low pressure steam turbine | 1 | b. Convert low pressure steam thermal energy into electricity |
| 6. | Air-cooled condenser | 1 | Condensate low pressure steam and recycled it to deaerator |

**Table 2. The components of the combined cycle/heat power (CCHP) plant**

| *No* | *Component* | *No* | *Component* |
|---|---|---|---|
| 1. | Gas turbine system | 4. | Drum |
| 2. | Furnace | 5. | Steam turbines (HP and LP) |
| 3. | Boiler (Riser, superheater, reheater, economizer) | 6. | Gas cooled condenser |

(i) Generation of exhaust gas from gas turbine systems
(ii) Generation of superheated steam by the high pressure superheaters
(iii) Evaporation of liquid water in the high pressure drums into high-pressure steam and its flow into the high-pressure superheaters and evaporators.
(iv) Heat extraction from exhaust gas to steam/water by heat exchangers
(v) Feedwater flow from deaerator to high pressure economizer and low pressure evaporator
(vi) Condensation of low pressured steam, after exiting the end point low pressure steam turbine and its feedback to deaerator.

These processes are not isolated from one another - changing the properties of one subsystem will effect the others, some of them are non-linear in nature.

On the macroscopic level, altering the macroscopic input variables e.g. fuel rate, air flow, make-up water flow to deaerator, coolant rate to condenser, would change the configuration of the microscopic inputs to each subsystem.

The microscopic inputs and outputs are localized to each subsystem i.e. internal to the plant, while the macroscopic inputs and outputs where global in nature i.e. the inputs to the systems came from external sources, and the outputs were not feedback into the plant system.

The combustion of fuel in the combustion chamber produces exhaust gas, which is then fed to the heat recovery steam generator (HRSG). A HRSG may consist of high-pressure (HP) superheater, HP evaporator, HP economizer and LP evaporator.

The superheater produces superheated steam to drive the high pressure (HP) and low-pressure (LP) steam turbines through the extraction of heat from the exhaust gas flowing across the superheater. The flow of steam from the adjacent high-pressure (HP) drum depends on the flow and enthalpy of the exhaust gas.

The HP and LP evaporator convert the liquid to saturated liquid into high pressure and low pressure saturated steam respectively through the absorption of heat from the exhaust, while the HP economizer absorbed heat and transferring it to the liquid water without it changing phases.

In the HRSG, the exhaust gas heat were transferred to the metal tubes in these heat exchangers by convection, which consequently transfer the recovered heat to the steam or water on its inner side.

The flow of the saturated steam from the adjacent high pressure drum to the high pressure (HP) superheater in the HRSG depends on the pressure drop across the HP superheater, which in turn depends on the properties of the steam and the properties of the exhaust gas flowing across the outer side of the metal tube of the heat exchanger of the HP superheater.

The dynamics of the saturated steam/liquid flowing across the heat exchangers depends on the dynamics of the exhaust gas, the metal tube temperature of the heat exchangers.

In combined cycle power plant, the (HRSG) provides the mechanism to generate superheated steam to the high pressure (HP) and low pressure (LP) steam generators, besides recovering waste heat from the exhaust gas exiting the gas turbine system. The HRSG recovers as much waste heat from the exhaust gas as possible, before the exhaust gas is released into atmosphere.

The saturated water from the drum is pumped into HP evaporator, where it is turned into steam upon receiving heat by convection from the exhaust gas. The feedwater pumped form the deaerator to HP economizer, which after receiving heat from the exhaust gas via the metal tube of the heat exchangers, flows into the HP drum.

The deaerator also supplies feedwater to LP evaporator by a pump, which after being turned into LP steam, is fed back to the deaerator. The deaerator also receives

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