# COMBINED CYCLE AND COMBINED HEAT AND POWER PROCESSES

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## Contents

## Summary

This article looks at Combined Cycle (CC) and Combined Heat and Power (CHP) processes for energy generation. In those processes heat energy and electrical energy are produced in one cycle, which enables more efficient energy usage than in systems with electricity and heat produced independently. Firstly, some typical configurations of CC/CHP processes are presented. Then, the main components are discussed. Combined Processes pose a challenge in terms of designing appropriate control system, which would take into consideration necessary co-ordination between the control of heat generation and the control of electricity generation. Also, those processes are required to be flexible in responding to changing demand (load). The typical control problems associated with Combined Processes and with their components are discussed in the article.

## 1. Introduction

The generation of electric power has become even more important over recent years. Due to the rising consumption and growing environmental awareness, new requirements have to be met. The power supply has to be constantly adapted to the stochastic requirements of the consumers, for the consumers of electric energy expect that they can use this energy at all times and in any quantity desired. However, the electric power cannot be stored in appreciable amounts. This means that it has to be produced at the time when it is needed. Differences between generation and consumption result in deviations from the adjusted target values of the network frequency and power delivered to customers.

Many large-scale industrial processes like refineries or chemical plants use very substantial amounts of electrical energy. In addition, very often, a hot water and/or steam is required for the chemical reactions and for heating purposes. A further task to be accomplished is to generate the thermal energy at a certain steam pressure and/or steam temperature, i.e. a certain “steam quality”. This makes building a local, combined heat and power (CHP) power station, on site, a sensible option. The CHP power station can utilize steam turbines, gas turbines, internal combustion engines or both steam turbines and gas turbines. In the latter case, it is called a Combined Cycle (CC) power plant. The CC/CHP plant offers the highest available efficiency in both commercial and industrial applications, where both power and thermal process demand are required.

**Combined Cycle (CC)** is a power plant system in which two types of turbines, namely a gas turbine and a steam turbine, are used to generate electricity. Moreover the turbines are to be combined in one cycle, so that the energy is transferred from one of the turbines types to another. The Combined Cycle can be used to produce only electricity or can be employed within the Combined Heat and Power scheme to produce both electricity and steam.

**Combined Heat and Power (CHP)** plant**,** sometimes called **Co-generation** plants**,** produce both electricity and heat. Heat is extracted as steam or hot water and exported from the system. Combined Heat and Power processes can be applied with conventional steam processes without gas turbines or may also include a Combined Cycle installation. Cogeneration or Combined Heat and Power (CHP) generation can be defined as the sequential use of a primary energy source to produce two forms of energy, basically heat and power at the same time.

A cogeneration system consists of six major components:

- A furnace converting chemical energy into heat energy
- Engine or turbine as a prime mover
- Generator which converts mechanical energy into electricity
- Heat exchangers
- Electrical switchboards
- Hydraulic interconnections

The fuel burned in the furnace is converted into thermal energy and then into mechanical energy of the steam. The fuel burned in the gas engine or gas turbine is converted into mechanical energy and thermal energy. The mechanical energy drives the generator to produce electricity.

Heat exchangers are installed to recover the thermal energy contained in the exhaust gases of the gas turbine, of the internal combustion engine, or of the steam generator, in the bleed steam or exhaust steam of the steam turbine, in the cooling water of the internal combustion engine jacket, in the lubrication oil and in the turbocharger. Up to 85 per cent of thermal energy can be utilized this way to generate steam or hot water.
Electrical equipment distributes the electricity. Pipe lines transport hot water or steam wherever it is required.

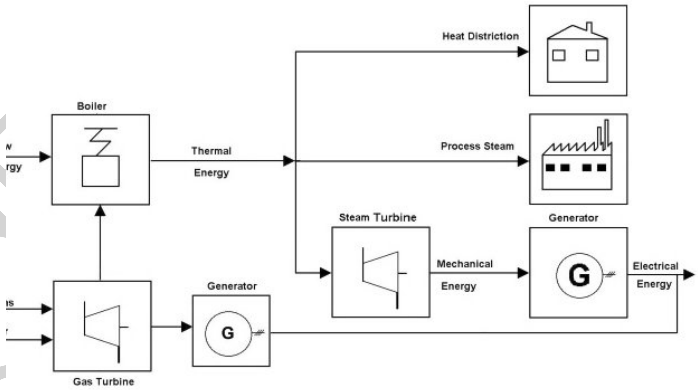

Figure 1: Schematic representation of a co-generation system.

### 1.1. Economic Justification for CC/CHP Power Plants

The CHP generating systems can be built in different ways depending on which prime mover (engine or turbine) and which fuel (gas, diesel oil, coal or waste) is used. The application of gas engines offers certain advantages. Among these are:

- High electrical efficiencies up to 40 per cent.
- High total efficiencies up to 85 to 91 per cent.

- Extremely low emissions due to the use of clean natural gas in combination with lean burning concepts or catalysts. Modern lean burning engine systems stay clearly below legal emission standards for thousands of operating hours without a catalyst to reduce $NO_X$ emissions.

Partial load efficiency and multi module plants make gas-engine cogeneration the most flexible cogeneration system. There are substantial efficiency losses on partial load operation and the interplay of different cogeneration units meets changing heat or electricity requirements. The whole system is flexible to minimize total energy costs for every day.

However, the gas engines are only available in the low range of output power. For medium to high power requirements, the gas turbines have to be used.

The advantages and the properties of cogeneration system with gas turbine are:

- Available in very high power range per module (1-300 MW)
- Exhaust gas temperature and mass flow rates are very high
- Variations in electricity frequency are small
- 2 or 3 kinds of fuel can be used in the same turbine.

Other types of fuel available for CHP plants have their own advantages. For instance, using waste or biomass as a fuel contributes to keeping the environment clean, especially around large cities. The fuel is also very cheap. However, the air pollution has to be closely monitored.

The internal combustion engines, run on diesel oil, offer an option of building small size CHP plant which may be appropriate for small, remotely located communities. However, the exhaust is not as clean as with gas turbines.

The conventional power supply (separate generation of electricity in thermal power stations, and heat in boilers) pollutes the environment and is uneconomical. In these systems approximately 60 per cent of the energy input is lost as waste heat. However, the waste heat which results during the generation of electricity by means of a gas engine or a gas turbine and generator could largely be utilized by heat exchangers and used for a various heating purpose such as hot water, steam, district heating, directly drying etc.

The simultaneous generation of heat and electricity by gas operated CHP plants achieves a total efficiency of about 90 per cent. Thus, the portion of energy losses is minimized. In total, more than 50 per cent of the energy input can be saved. Figure 2 gives an example of comparison of production of electrical and thermal energy in a cogeneration and a conventional system. In this figure, energy production for a factory, which needs 34 units of electrical energy and 53 units of thermal energy, is compared for two types of power plants (thermal and cogeneration). It is assumed that the same electrical efficiency can be obtained for a condensing power plant and for a CHP plant. As shown, energy production with cogeneration power plants causes 37% primary energy savings. In practice, those savings can be slightly lower, as a power plant for electricity production can have a higher efficiency (up to 55%).

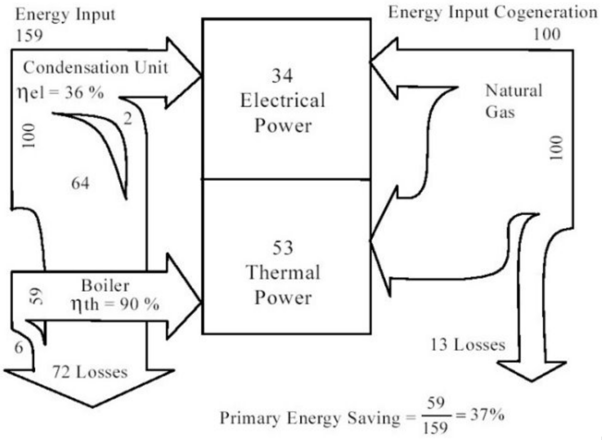

Figure 2: Comparison of production of electrical and thermal energy in a co-generation and a conventional system, for primary energy savings.

### 1.2. Environmental Justification for CC/CHP Power Plants

Environmental pollution that stems from energy generation is often directly proportional to the amount of fuel burnt. For this reason a better usage of fuel can reduce fuel consumption and thereby reduce pollution. On the other hand, if waste can be reduced higher energy outputs can be achieved for the same levels of pollution. The combined heat and power and combined cycle power systems offer this possibility. It does of course depend upon the particular circumstances but if, for example, a gas turbine driven power generator is needed because of the rapid start-up time combining this with a coal fired boiler system in a combined cycle configuration can provide an efficient system with reduced environmental impact, whilst still addressing the operational demands.

## 2. Elements of Combined Cycle / Combined Heat and Power Processes

### 2.1. Gas Turbine

A gas turbine is a machine, which converts the energy of burning gas into the rotational energy of its shaft. The gas burning in the combustion chamber expands and exerts pressure on the turbine blades, causing the shaft to rotate. A compressor provides the air necessary for combustion, whose blades, will normally be on the same shaft as the turbine blades.

The main components of a gas turbine (Fig. 3) include: a compressor with an air inlet, a combustor with fuel (gas) supply system, a turbine, an exhaust gas duct and a cooling system. It is possible to add some other turbines and compressors into the system, and intercooler between the compressors, an inter-heater between the turbines, a heat exchanger before entering the combustion chamber in order to preheat the gases using some of the exhaust gas energy.

While such equipment increases the system efficiency and power; it also increases the weight, the cost and the dimensions.

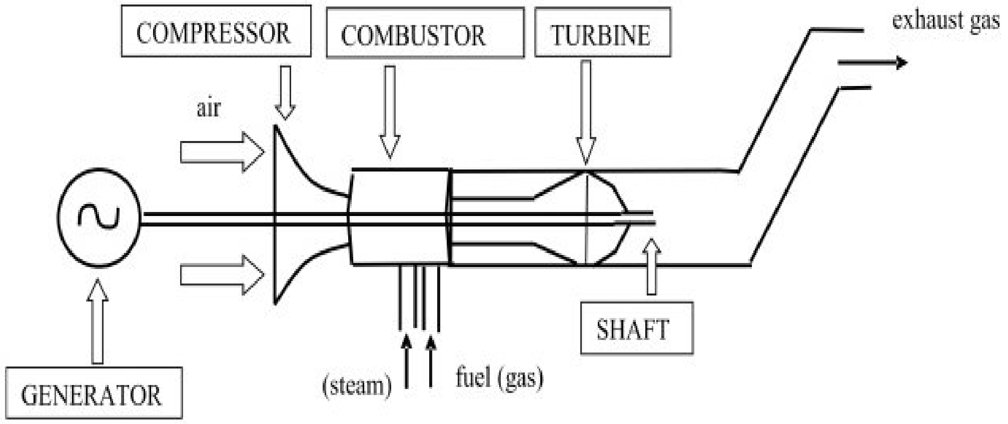

Figure 3: Schematic diagram of a Gas Turbine.

Contemporary gas turbines produce electric power in a range up to 300 MW, and the outlet gas temperature is around 550°C while the combustion gas temperature may exceed 1200°C.

There are about 100 companies today manufacturing around 600 models of gas turbines. The power outputs range from 2-3 kW of model planes to 300 MW of complex electric plant systems, their fuel consumption per kilowatt ranges from 0.220kg/kWh to 0.880kg/kWh with the efficiencies varying 25%-40%. In addition, their pressure rates range from 2.5:1 to 16:1.

### 2.1.1. Classification

Taking into account various features, gas turbines can be classified as follows.

With respect to heating method: Constant volume gas turbines and Constant pressure gas turbines.

With respect to the type of cycle: Open system gas turbines (used in majority of applications), Closed system gas turbines, Combined system gas turbines (Fig. 4).

With respect to the mechanical arrangements: Single shaft gas turbines, Two or more shafts gas turbines, Distinct power turbines (without inter heater), Serial flow (with interheater) gas turbines, Parallel flow (with two combustion chambers) gas turbines (Fig. 5).

With respect to the equipments used: Basic gas turbines, Gas turbines with regenerators, Gas turbines with intercooler, Gas turbines with interheater, Complex (interheater, intercooler and regenerator) gas turbines.

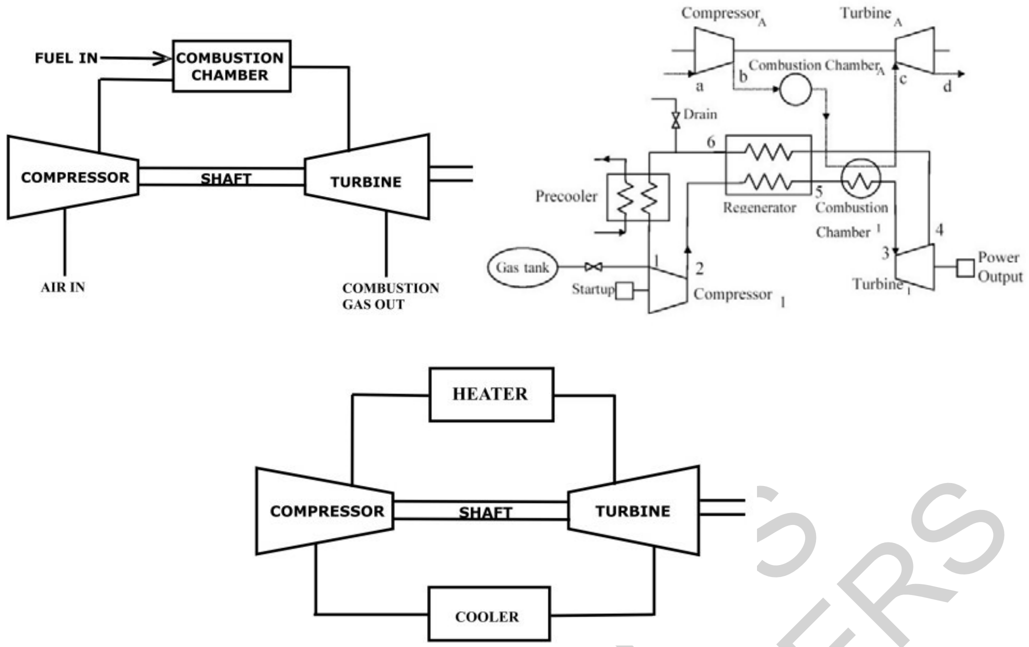

Figure 4: Open, closed, and combined system gas turbine.

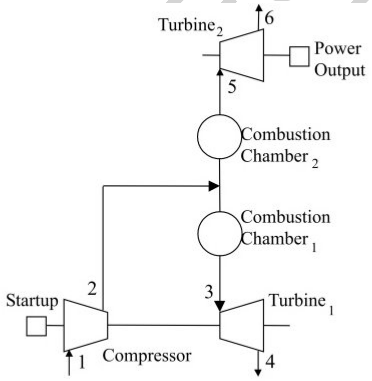

Figure 5: Parallel flow gas turbine.

### 2.1.2. Properties of Gas Turbines

*Heating and start-up time***:** Cold gas turbines are heated in a period of 6-15 minutes following the start-up. There is no need for a heating period of 1-1.5 hours as in the steam turbines.

*Configuration simplicity***:** The turbine rotor is the rotational part of the system. Therefore, there are no unbalanced forces and vibrations caused by these forces. The combustion chamber is cheap and light.

*Dimensions and machine density*: The space occupied per unit power in gas turbines (0.02-0.61 sqft/kW) is less than those in steam turbines (<0.1 sqft/kW). Having a greater power from a smaller space and a less machine weight per kilowatt produced in this machine is an important feature. Dimensions of gas turbines for low powers are quite greater than those of high-spin diesel engines. However, gas turbines are more advantageous than diesel engines for high powers regarding their dimensions. *Independence*: Comparing with the steam turbines with condensers, the gas turbines (except combined cycle) do not need water at all. They only need some water to cool the air in inner cooling cycles. The gas turbines do not require accumulators if their initial movement is supplied by compressed air. *Lubrication*: The parts requiring lubrication in gas turbine systems are compressors, turbines and bearings. In diesel engines, a complicated lubrication circuitry and special lubrication oil are required.

## 2.2. Boiler

The boiler is a part of a power plant, which produces steam. The water enters the boiler and goes through a stage of preheating in the economizer, exchanging energy with the combustion gases. The evaporation process occurs in the risers and the water/steam mixture circulates though the risers passing the combustion chamber. The separation of vapor and water is taken place in the drum. Modern combined cycle plants have boilers with 2 or 3 pressure stages and correspondingly 2 or 3 drums. The steam from the drum is extracted into the super-heater section and from there enters the steam turbine. The reheater section is used to reheat the steam between two stages of the steam turbine. In contemporary combined cycle power plants, the boiler is a pure heat recovery steam generator. The exhaust gases are used to heat water in a boiler to raise steam. The boiler may not have the combustion chamber since the energy from the gas turbine exhaust temperature is sufficient to convert water into steam. In addition, the boiler can have various auxiliaries, such as burners, fans, emission control equipment, and stack.

Boilers are used in both fossil and nuclear fuel power plants. Modern boilers produce high-pressure (2400 to 3500 psia, 165 to 240 bar) superheated steam, the exception being pressurized-water reactor steam generators, which produce lower-pressure (1000 psia, 70 bar) saturated steam. Boilers represent by far the greatest energy converters for power plants in the world today.

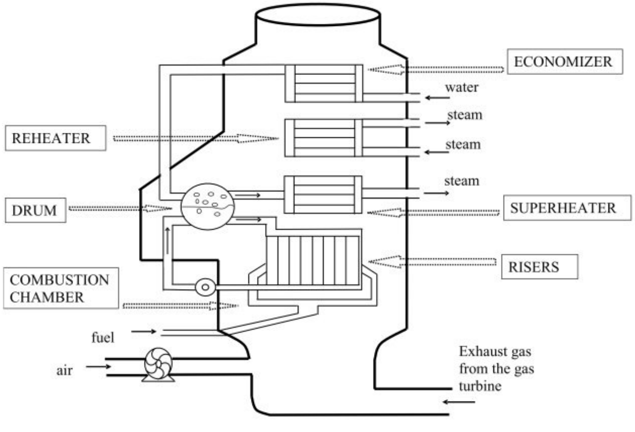

Figure 6: Schematic diagram of a boiler.

Types of boilers include:

- Fire-tube boilers,
- Water-tube boilers,

- Natural-circulation boilers,
- Controlled-circulation boilers,
- Once-through flow,
- Subcritical,
- Supercritical.

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## Bibliography

Ahluvalia K.S. and R. Domenichini. (1990). Dynamic modelling of a combined cycle plant. *Trans. ASME Journal of Engineering for Gas Turbines and Power***. 112**, 164-167.[This paper presents a dynamic model of a combined cycle plant]

Åström K.J. and R.D.Bell. (1988). Simple drum boiler models. Proc. IFAC *Power Systems Modelling and Control Applications*. Brussels. [This paper presents simple dynamic models of a drum boiler]

Balchen J.G. and K.I. Mummé. (1988). *Process Control Structures and Applications.* Van Nostrand Reinhold Company Inc.. [This book discusses ctructures of control systems in process industry and illustrates this on selected applications]

Basu R.N. and L.L. Cogger. (1986). Integrated approach to cogeneration planning, control and management. Proc. IFAC Symposium *on Automation and Instrumentation for Power Plants*. [The paper shows an integrated structure for control and management of co-generation plant]

Bransby M.L. (1982). Direct digital control in CEGB Power Stations. Chapter 9 of *Computer Control of Industrial Processes*, (Eds. Bennet S., and D.A. Linkens), pp. 155-169. Peter Peregrinus Ltd. Stevenage, UK. [This contribution discusses direct digital control of CEGB power stations].

Cegrell T. (1986). *Power System Control Technology.* Prentice Hall International. [This book presents control technology used in Power Systems]

Çetinkaya, S. (1997). *Gas Turbines*. Nobel Yayın Dağıtım. Turkey. (in Turkish)

Cohen H., G.F.C. Rogers and H.I.H. Saravanamuttoo. (1987). *Gas Turbine Theory* (3rd edition). Longman. [This book describes functioning of gas turbines]

Conradie F.H. and H. Kurten. (1992). Actual dynamic performance of thermal power plants with various designs and control systems. Proceedings of the IFAC Symposium on *Control of Power Plants and Power Systems*, Munich. [This article discusses how the design of control system affects the dynamic performance of a power plant].

El-Wakil, M. M. (1984). *Power Plant Technology*, McGraw-Hill, Singapore,

Gunn, D. and Horton, R. (1989). *Industrial Boilers,* Longman,.

Hussain A. and H. Seifi (1992). Dynamic modelling of a single shaft gas turbine. Proceedings of the IFAC Symposium on *Control of Power Plants and Power Systems*, Munich. [This paper presents a dynamic model of a single shaft gas turbine]

Hung W.W. (1991). *Dynamic simulation of gas-turbine generating unit.* IEE Proceedings-C, **138**, 4

IEEE Committee. (1991). *Dynamic models for fossil fueled steam units in power system studies.* IEEE

Trans. on Power Systems, **6**, 2, 753-761.

IEEE Committee (1972). *Dynamic models for steam and hydro turbines in power system studies.* IEEE Committee Report, IEE PES Winter Meeting, New York

Kapadia M. and C.H. Wolgemuth. (1984). A dynamic model of a condenser in a closed Rankine cycle power plant. Proc. American Control Conference

Klefenz, G. (1981). *Automatic Control of Steam Power Plants*, Germany

Kure-Jensen J. and R. Hanisch. (1991). Integration of steam turbine controls into power plant systems. *IEEE Trans. on Energy Conversion*, **6**, 1, 177-185.

Mann J. and G.K. Lausterer. (1992). Temperature control using state feedback in a fossil fired power plant. Proceedings of the IFAC Symposium on *Control of Power Plants and Power Systems*, Munich. [This paper describes a new method of temperature control in a boiler]

de Mello F.P. (1991). Boiler models for system dynamic performance studies. *IEEE Trans. on Power Systems*, **6**, 1, 66-74. [This article describes mathematical models of boilers, widely used and referenced]

de Mello F.P., R.J. Mills and W.F. B'Rells. (1973). Automatic generation control, part I: Process modeling, part II: digital control techniques. *IEE Transactions on Power Apparatus and Systems*, **PAS-92**, 2, 710-725,

Nakanomori K. and M. Kano. (1992). On the automatic start-up/shutdown system for a combined cycle with two different gas turbines. Proceedings of the IFAC Symposium on *Control of Power Plants and Power Systems*, Munich. [This paper discusses a specific problem of control for a combined cycle power plant].

Norman, H.B. and P.J.E.Rubbers. (1980). A generation expansion program to achieve optimum plant mix and minimum cost of a fixed reliability of supply, Proc. *IFAC Symposium on Automatic Control in Power Generation, Distribution and Protection*, pp 553-558,.

Polimeros G. (1981). *Energy Cogeneration Handbook.* Industrial Press Inc. [This book describes the principles of co-generation]

Rowen W.I. (1988). *Speedtronic Mark IV control system.* Alsthom Gas Turbine Reference Library (AGTR 880). [This article describes a specific control system for a gas turbine].

Rowen W.I. (1983). Simplified mathematical representations of heavy-duty gas turbines. *ASME Journal of Engineering for Power*, 865-871.

Thermoflow Inc. (ed.) (1991). *Design of gas turbine combined cycle and cogeneration systems.* Lecture notes from the course in St Albans, England, July 31-August 2.

Vahldieck R. and H. Krause. (1986). Practical experience with progressive automation concepts in power plants. Proc. IFAC Symposium on *Automation and Instrumentation for Power Plants*

Waddington J. and G.C. Maples. (1987). *The control of large coal- and oil- fired generating units.* Power Engineering Journal, pp 25-34

Welfonder E. (1992). Constrained control concepts in power plants and power systems for avoiding emergency conditions. Proceedings of the IFAC Symposium on *Control of Power Plants and Power Systems*, Munich. [This article provide an overview of control configurations for fossil fuelled power systems].

Wildi T. *Electrical Power Technology.* (1985). Wiley, New York. [This book discusses various aspects of power generation].

Yacobucci R.B. (1991). A control system retrofit for a GE frame 5 turbine/generator unit. *IEEE Trans. on Energy Conversion*, **6**, 2, 225-230. [This article describes the process of upgrading a gas turbine control system].

**Biographical Sketches**

**Dr. Andrzej W. Ordys** is the British Energy Lecturer in Control Systems and the Technical Manager of the Industrial Control Centre at the University of Strathclyde, Glasgow, UK. His current research interests are in optimal predictive control, modeling and simulation of power plants and implementation of advanced process control algorithms. He develops theory and algorithms for benchmarking performance of controllers. He has been involved in the theoretical development of stochastic and predictive control theory. He has contributed to a range of industrial application projects including those for the power, defense and metal processing industries. He has co-authored two books related to modeling, simulation and control of power stations. He has been involved in management of many research projects especially with large international participation. He was coorganizer of several tutorial workshops at IEEE Conferences. Dr. Ordys is Member of IEE and Chartered Engineer, and Member of IEEE and of IAPR.

**A.W. Ordys** is Professor of Automotive Engineering at Kingston University, London. Previously he worked at the University of Strathclyde as the British Energy Senior Lecturer in Control Systems in the Department of Electronic and Electrical Engineering.

His current research interests include control and optimisation of engine power train, embedded systems in automotive applications, hybrid control of fast and high-precision mechanical systems and performance assessment of control systems.

He has been contributing to the theoretical development of stochastic and predictive control theory and the theory of benchmarking control algorithms.

He has been involved in management of many research projects especially with large international participation.

He has contributed to a range of industrial application projects including those for the automotive, power, oil and gas, chemical, defence and metal processing industries.

Dr. Ordys is Member of IEE and Chartered Engineer, and Senior Member of IEEE. He is a past Chairman of EC&I Section of IEE Scotland.

He has been member of International Programme Committee for many international conferences, most recently for IEEE American Control Conference 2005, IASTED Control Applications Conference 2005 and IASTED Modelling Identification and Control Conference 2005, IEEE Conference onControl Applications, Taiwan, June, 2004. He is a member of the Organising Committee of UKACC Control 2006 Conference.

**Prof. Michael J. Grimble** was born in Grimsby, England. In his formative years he acquired a BSc (Coventry), MSc, PhD and DSc degrees from the University of Birmingham. In 1981, The University of Strathclyde, Glasgow, appointed him to the Professorship of Industrial Systems and he is now the Director of the Industrial Control Centre. Shortly after his appointment he established the forerunner of the Industrial Control Centre which has grown rapidly to be one of the largest self-financing industrial control centers in Europe. It attracts a sequence of leading researchers and Visiting Professors from around the world and provides a large research school in advanced systems. His Centre is concerned with industrial control problems, particularly those arising in the Aerospace, Manufacturing, Process Control, Wind Energy, Metal Processing, Marine, Electrical Power and Gas industries. His research interests include self-tuning, $H_\infty$ robust control theory, multivariable design techniques, optimal control and estimation theory. The Centre has an income of about £1.5 million and there are approximately forty research students, engineers and visiting academics.

He is the Managing Editor of the *International Journal of Adaptive Control and Signal Processing* published by John Wiley Ltd. He is also the Managing Editor of the Wiley *International Journal of Robust and Non-linear Control*. He is the editor of the Prentice Hall International series of books on *Systems and Control Engineering* and also the Prentice-Hall series on *Acoustics Speech and Signal Processing.* He is a joint editor of the Springer Verlag Monograph Series on *Advances in Industrial Control* and is an Editor of the Springer *Lecture Notes in Control and Information Sciences* series.

The Institution of Electrical Engineers presented him with the *Heaviside Premium* in 1978 for his papers on control engineering. The following year, 1979, he was awarded jointly the *Coopers Hill War Memorial Prize and Medal* by the Institutions of Electrical, Mechanical and Civil Engineering. The Institute of Measurement and Control awarded him the 1991 *Honeywell International Medal*. He was awarded an *IEEE Fellowship* in 1992 and he was recognized at the 1993 Edinburgh International Science Festival as one of Scotland’s four most cited Scientists. He was recently appointed a Fellow of the Royal Society of Edinburgh.

**Prof. İlhan Kocaarslan** was born in Kırıkkale, Turkey, in 1964. He acquired his BSc and MSc degrees from Yıldız Teknik University, İstanbul, in 1983 and 1985 respectively, then PhD degree from Ruhr University Bochum , Germany, in 1991. During his PhD and afterwards, until 1997 he worked for Babcock Prozessautomation Gmbh, Germany. He worked there as the Head of Automation Engineering Department and he was concerned with many projects including establishment, automation and improvements of several power plants and waste incineration plants in Germany, Greece, Taiwan, China, Czech Republic, United Arab Emirates and Turkey.

In 1997, he joined Kocaeli University, Turkey, as an Associate Professor. In 1999, Kırıkkale University, Turkey, appointed him to Professorship and he became the Head of the Department of Electrical and Electronic Engineering. He is also the Dean of Engineering Faculty in Kırıkkale University since March 2002. His research interests are Process Control of Cogeneration Plants, Modeling and Adaptive Control of Combined Cycle Power Plants, Temperature Control of Fluidized Bed Combustion Power Plants and Waste Incineration Plants.