Analysis of Gas Turbine Systems for Sustainable Energy Conversion

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Abstract

Increased energy demands and fear of global warming due to the emission of greenhouse gases call for development of new efficient power generation systems with low or no carbon dioxide (CO₂) emissions. In this thesis, two different gas turbine power generation systems, which are designed with these issues in mind, are theoretically investigated and analyzed.

In the first gas turbine system, the fuel is combusted using a metal oxide as an oxidant instead of oxygen in the air. This process is known as Chemical Looping Combustion (CLC). CLC is claimed to decrease combustion exergy destruction and increase the power generation efficiency. Another advantage is the possibility to separate CO₂ without a costly and energy demanding gas separation process. The system analysis presented includes computer-based simulations of CLC gas turbine systems with different metal oxides as oxygen carriers and different fuels. An exergy analysis comparing the exergy destruction of the gas turbine system with CLC and conventional combustion is also presented. The results show that it is theoretically possible to increase the power generation efficiency of a simple gas turbine system by introducing CLC. A combined gas/steam turbine cycle system with CLC is, however, estimated to reach a similar efficiency as the conventional combined cycle system. If the benefit of easy and energy-efficient CO₂ separation is accounted for, a CLC combined cycle system has a potential to be favorable compared to a combined cycle system with CO₂ separation.

In the second investigation, a solid, CO₂-neutral biomass fuel is used in a small-scale externally fired gas turbine system for cogeneration of power and district heating. Both open and closed gas turbines with different working fluids are simulated and analyzed regarding thermodynamic performance, equipment size, and economics. The results show that it is possible to reach high power generation efficiency and total (power-and-heat) efficiency with the suggested system. The economic analysis reveals that the cost of electricity from the EFGT plant is competitive with the more conventional alternatives for biomass based cogeneration in the same size range (<10 MW).
List of Appended Papers

This thesis is based on the following papers, referred to by Roman numerals I-VII.

[I] Chemical-Looping Combustion - Efficient Conversion of Chemical Energy in Fuels into Work
Anheden, M., Nåsholm, A.-S., Svedberg, G.

[II] Chemical-Looping Combustion in Combination with Integrated Coal Gasification
Anheden, M., Svedberg, G.

[III] Exergy Analysis of Chemical-Looping Combustion Systems
Anheden, M., Svedberg, G.

[IV] Aspects on Closed Cycle Gas Turbines. Literature Report
Anheden, M., Ahlroth, M.
Royal Institute of Technology, Dept. of Chemical Engineering & Technology, Energy Processes, 1997, TRITA-KET R73, ISSN 1104-3466, ISRN KTH/KET/EP--73--SE

[V] System Studies on a Biomass Fired CHP Closed Cycle Gas Turbine with a CFB Furnace
Anheden, M., Ahlroth, M.

[VI] Externally Fired Gas Turbine Cycles for Small Scale Biomass Cogeneration
Anheden, M., Ahlroth, M., Martin, A.R., Svedberg, G.

Anheden, M., Martin, A.R.
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The papers are appended at the end of the thesis.
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1 Introduction

The world’s energy demand is projected to grow significantly over the next 20 years. This increase will be a result of economic growth, industrial expansion, high population growth, and urbanization, especially in the developing countries. The major part of this energy demand is believed to be met by using non-renewable fossil fuels with a limited supply. As a global community, the question we have to face is: **How can we provide the energy service demanded by growing populations, yet reduce the total primary energy from non-renewable energy sources?**

Two technological solutions that have been suggested are:

- To increase the energy conversion efficiency of existing and future energy conversion processes by various technological advancements. This decreases the fuel consumption per unit of activity.
- Promote and further develop use of renewable energy sources like solar, wind and biomass.

Another important issue is the environmental impact associated with energy conversion. Until a few years ago, the primary concern about energy impacts on the environment was of a local nature. The focus was on the negative consequences of mining these fuels and the emissions of sulfur oxides (SO₂), nitrogen oxides (NOₓ), and uncombusted hydrocarbons. Today, there is an increased awareness of the likeliness of a global climate change associated with emissions of so-called greenhouse gases. The emission of carbon dioxide, CO₂, from combustion of fossil fuels is now identified as a threat to the global population. The challenge that we have to meet is:

**How can we decrease the CO₂ emissions to the atmosphere associated with energy conversion?**

Possible strategies to resolve this problem include:

- Increase the energy conversion efficiency of existing and future energy conversion processes.
- Increased utilization of energy sources with lower carbon intensity, i.e. use of fuels that emit less CO₂ per unit of useful energy.
- Increased utilization of CO₂-neutral energy sources.
- Capture and sequestration of CO₂ from power plants and other sources before it is emitted to the atmosphere.
- Increased carbon sequestration by enhancing natural sinks, such as the terrestrial biosphere and the oceans in up-take and storage of carbon.

The studies presented in this thesis originate from the two questions stated above. The overall objective is to investigate power plants that provide for a high fuel conversion efficiency. The plants studied also directly reduce the emissions of CO₂ by either providing for energy efficient capture of CO₂ or utilizing a CO₂ neutral fuel.
Another common theme is that the investigated systems involve gas turbine-based power generation.

1.1 Scope of the Work

The objective of the first study, Papers I-III, is to investigate the possibilities of decreasing the destruction of "useful energy" (also called exergy), on combustion with a novel combustion process called Chemical Looping Combustion (CLC). Decreased exergy destruction during combustion would provide possibilities for an increased overall efficiency of the power generation process. Chemical Looping Combustion also makes possible easy and energy conserving separation of the CO₂ formed on combustion of the fuel.

In Paper I, a gas turbine system with methane as the fuel and NiO as the oxygen carrier in the Chemical Looping Combustion system is studied from a thermodynamic point of view. The calculated performance of the CLC gas turbine system is compared to the performance of a similar system with conventional combustion. This study is repeated with Fe₂O₃ as oxygen carrier in a MS Thesis project under supervision of the author (Welin-Berger, 1995). In Paper II, a study on a CLC gas turbine system with gasified coal as the fuel is presented. The performance of the system, when using different oxygen carriers is evaluated. The third paper, Paper III, is focused on exergy analysis of the systems presented in Papers I and II. The works in Papers I-III are summarized in Chapter 4 in this thesis.

The second study, Papers IV-VII, explores gas turbine based cogeneration of power and heat from a renewable, CO₂-neutral biomass fuel. The objective of the study is to reach both a high electric and total efficiency in a small-scale plant. This is to be accomplished at a competitive cost of the generated electricity. The plants studied contain closed and open externally fired gas turbines.

Paper IV summarizes the previous theoretical work on closed cycle gas turbines (CCGT) and operating experience from actual plants built. Paper V presents results from a thermodynamic analysis of a small-scale CCGT plant with a biomass fired circulating fluidized bed (CFB) furnace. The variations in performance when using different working fluids - N₂, He and mixture of He and CO₂ - are reported. In Paper VI, the thermodynamic analysis in Paper V is complemented with an investigation of the dependency of working fluid selection on the equipment size. In addition, the study is supplemented with a comparison between open and closed cycle gas turbines. An economical analysis of the gas turbine systems in Papers V and VI is finally introduced in Paper VII. The differences between the gas turbine cycles, both in equipment size and performance, related to the selection of working fluid and configuration are translated into economic terms. A comparison is also made between the proposed gas turbine system and conventional and emerging technologies for small-scale biomass cogeneration. The investigations in Papers IV-VII are summarized in Chapter 5 of the thesis.
2 Background

This chapter will give the reader some general background on the world's present fuel consumption and its projection for future use, with an emphasis on the power generation sector. The greenhouse effect and different options to reduce CO₂ emissions from the power generation industry are briefly discussed. Finally, special implications related to solid biomass fuel utilization are introduced.

2.1 World Fuel Consumption and Energy Utilization

Driven by increasing population and economic growth, global demand for energy is increasing. By extending past trends of energy consumption into the future, the International Energy Agency, IEA, projects that the global primary energy consumption is going to increase from about 110 000 TWh (or 9 400 Mtoe) in 1996 to 160 000 TWh (or 13 700 Mtoe) in 2020. This implies substantial growth in energy demand and CO₂ emissions. The main sources of energy today are fossil fuels like oil, coal, and natural gas. These fuels are thought to continue to supply the major part of the world's energy demand in the foreseeable future, with an increase in the use of natural gas (IEA, 1998).

In the utilization of energy, IEA projects that the demands for electricity and transport will continue their upward trends. Fossil fuel demand for stationary services (mainly heating of buildings and processes) tend to flatten out in OECD regions but continues upward in China and developing countries as industrialization increases rapidly. The energy demand for power generation follows electricity demand, but is slightly reduced as new generating plants with higher efficiency are introduced.

Regarding power generation, an increased use of natural gas is foreseen by IEA. However, coal based power plants are still expected to supply the main capacity in the power generation sector. Electric power generation from renewable fuels is expected to increase but is still at a low level.

These forecasts do not account for policy changes, changes in the economic growth rate, or the estimated resources and reserves of respective fuels as well as any new technological breakthroughs in the power-generating sector. However, changes in these sectors over the next couple of years will have a significant impact on the future energy system. It is therefore important that we are aware of this fact when making decisions, so that we can provide for sustainable development.

2.2 The Greenhouse Effect and CO₂ Mitigation

Human activity in the modern world has disturbed the composition of the atmosphere. This has led to some of the major environmental issues of our time - ozone depletion, acid rain, and now global warming/climate change due to the enhanced greenhouse effect.
Activities resulting in emission of extra amounts of greenhouse gases, especially CO₂, N₂O, CH₄ and CFCs, alter the amounts of radiation trapped by the atmosphere and therefore may have an effect on climate. Measurements show that the concentration of CO₂, for instance, has increased from a pre-industrial concentration of about 280 ppmv to 358 ppmv in 1994 (Adams et al., 1997). Recordings also show that the average temperature on earth has increased by about 0.3° to 0.6°C since the late 19th century - when these instrumental records began. The natural variations in temperature make it difficult to scientifically prove this temperature increase; however, in 1995 IPCC (UN's international expert panel for climate issues) concluded that “the balance of evidence suggests a discernable human influence on the global climate”.

If the rate of climate change can be limited, then human societies and ecosystems will find it easier to adapt. The way to slow the rate of change is to reduce emissions of greenhouse gases. In December 1997, climate change negotiators representing 155 parties to the UN Framework Convention on Climate Change met in Kyoto, Japan. They left the conference with a protocol for subsequent signature and ratification by parties, stating reduction of 1990 or 1995 emission levels of six greenhouse gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) by year 2008-2012. For example, the EU commitment is to reduce the emissions by 8% and the USA by 7% (Jefferson, 1998).

Of all the greenhouse gases, CO₂ contributes the most (about 55%) to the increased greenhouse effect, if both the concentration and how much the gas contributes to the greenhouse effect are taken into account. One of the largest sources of CO₂ emissions is power generation using fossil fuels. In the EU and the United States, the power generation sector contributes with approximately 1/3 of the total CO₂ emissions. In Sweden, the contribution from the power generation sector is lower (about 18%) since the dominating part of electricity is generated in nuclear power plants or hydro power plants almost without any CO₂ emissions. A contrast between CO₂ emissions in Sweden and the USA, based on the source, is shown in Figure 2.1.

In the future, the share of global CO₂ emission from the power industry sector may increase due to the industrialization of the developing countries and continued electrification of the industrial and building sectors in the developed countries.

![Figure 2.1 CO₂ Emissions from fuel combustion by sectors in Sweden (total 52.7 Mtonnes CO₂) and USA (total 5375 Mtonnes CO₂), year 1997 (UNFCCC, 1999).](image-url)
On a longer-term perspective, even the transportation sector may be electrified. Therefore, ways of reducing CO₂ emissions from power plants are now being investigated.

There are a variety of options available for reducing greenhouse gas emissions. In most cases, the least expensive options involve reducing emissions at the source — for example, improving the efficiency of using fossil fuels. The fuel utilization can also be increased through cogeneration of heat and power. Substitution, e.g., replacing a high carbon fuel with a low carbon fuel, can achieve useful reductions at relatively low cost, where supplies are available. However, to make deep reductions in emissions typically requires more extended measures such as changing from fossil fuels to renewable sources, for instance utilization of biomass fuels. Enhancement of the natural sinks of carbon, such as the oceans and forests, has also been discussed.

Only in the past few years has serious considerations been given to technologies which would allow deep reductions in greenhouse gas emissions while continuing to use fossil fuels, the so-called carbon sequestration option. Carbon sequestration can be defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere. The idea is to keep carbon emissions produced by human activities from reaching the atmosphere by capturing and diverting them to secure storage, or to remove carbon from the atmosphere by various means and store it. Carbon sequestration should be seen as a complement to the strategy of improving efficiency and increasing the use of non-fossil fuels. In particular, the option of capturing the CO₂ emitted at the power plant on combustion is seen as technically feasible and could be implemented relatively quickly. The captured CO₂ would then be disposed in the deep ocean and geological formations like deep aquifers, exhausted gas and oil reservoirs, and unmineable coal seams. Atmospheric carbon can also be captured and sequestered by enhancing the ability of terrestrial or ocean ecosystems to absorb it naturally and store it in a stable form. These options are considered to be able to store the anthropogenic CO₂ emissions over a vast amount of time (Herzog and Vukmirovic, 1999).

However, the option of CO₂ capture and storage provide a number of challenges that must be addressed. One challenge is to reduce the cost and efficiency penalty associated with capture. Various options for CO₂ separation from power plants are presently being investigated. Another challenge is to verify the feasibility of CO₂ storage in various geological and ocean reservoirs. This includes understanding of the long term fate of the CO₂ and addressing environmental and safety concerns.

2.3 Biomass Energy

Renewable energy is any energy source that can be either replenished continuously or within a moderate timeframe. These energy supplies can be endless resources such as the sun, the wind, and the heat of the earth, or they can be replaceable such as plants. In contrast, fossil fuels like oil, coal, and natural gas form so slowly in comparison to our rate of energy use that they are considered finite or limited resources.

Renewable power generation sources include solar power, biomass power, wind power, hydropower, and geothermal power. Biomass power is one of the most
favorable sources in this category for a number of reasons. With proper harvesting practices, biomass is a sustainable resource that can be found in most regions of the world. The combustion of biomass produces nearly zero net \( \text{CO}_2 \) emissions and, with clean combustion techniques, emits low levels of unburned hydrocarbons, \( \text{NO}_x \), and \( \text{SO}_2 \). Figure 2.2 illustrates the biomass fuel utilization cycle.

Fuels included in the biomass category are mainly wood (logs, bark, sawdust, and energy plantations), straw, energy grasses, and digester liquors from pulp mills. Sometimes refuse and peat are included in this category. In the industrialized countries, biomass fuels are used in four main areas - the forest product industry, district heating plants, the residential sector, and electricity production - while in developing countries, biomass is mostly used for cooking and heating.

The use of biomass energy for power generation has increased over the last decade. Most biomass power plants operating today are using a steam boiler and steam turbine. The majority of plants is used for combined heat and power generation. Grate firing is dominating but development of the fluidized bed combustion technology has made it possible to increase the utilization of various biomass and waste products in both power and heat generation.

A number of different new technologies are presently being developed for biomass based power generation to increase the power conversion efficiency. The main R&D challenges connected to biomass based power production include resolving issues around ash chemistry, \( \text{NO}_x \) reduction, improving materials, and developing sufficient energy crops for feedstocks. Long term demonstrations of advanced technology concepts are also necessary.

![Figure 2.2 Biomass based power generation and the carbon and mineral cycle (from Yan et al., 1997).](image)
3 The Gas Turbine

Gas turbines are selected as the prime mover for power generation in both studies in this thesis. The main reason for this selection is that gas turbines are able to operate at a high efficiency when utilizing a high temperature heat source. The focus in this chapter is on special gas turbine related issues important to the studies in Chapter 4 and 5, e.g. the special characteristics of closed cycle gas turbines, the technologies available for using solid fuels, and the approaches for separating CO₂.

3.1 Introduction

A simple gas turbine is comprised of three main sections: a compressor, a combustor and a turbine. The gas turbine operates on the principle of the Brayton cycle where compressed air is mixed with fuel and burned under constant pressure conditions. The resulting hot gas is expanded through a turbine to perform work.

The simple cycle gas turbine power plants designed to be suitable for electric utility applications have the advantage of high power output for a relatively small size and weight, low initial cost, rapid installation, short start-up times, fuel flexibility, and zero water consumption for cooling. A typical gas turbine for electric utility applications has a power output range between 50 kW and 240 MW.

In the past, one of the major disadvantages of the gas turbine was its low efficiency compared to other internal combustion engines and steam turbine power plants. However, continuous engineering development work has pushed the electric efficiency from 18% for the first gas turbine in commercial operation, the 1939 Neuchatel gas turbine, to present maximum levels of about 40% for simple cycle operation. Improvements of the simple cycle and additions of steam turbine bottoming cycles are capable of further increasing the efficiency. Today, a combined gas turbine, steam turbine cycle is capable of achieving an efficiency of almost 60%. Figure 3.1 shows a timeline of the development of power generation technology.

The improvements of the gas turbine cycle have historically been aiming at increasing the efficiency, lowering the investment cost, and reducing environmental emissions. To increase efficiencies, turbine designers have worked to increase firing temperatures without damaging the turbines. However, firing turbines beyond the threshold temperatures of their components threaten their integrity and reliability. Development of advanced cooling techniques and improving materials are two major strategies of solving this problem. The improvements of the individual efficiencies of the main gas turbine components like the compressor and turbine have also helped in increasing the gas turbine efficiency. In addition, improved efficiency can be achieved by modifications to the original simple cycle to recover heat from the turbine exhaust. Examples of this kind of modifications are recuperated gas turbines, exhaust gas heat recovery for generation of steam in a steam turbine bottoming cycle,
the STIG cycle, the HAT cycle, and the chemically recuperated cycle. Descriptions of these advanced configurations can, for instance, be found in Korobitsyn (1998).

3.2 The Closed Cycle Gas Turbine

The gas turbine working fluid circuit can be arranged in two ways: either with an open circuit or a closed circuit. In the closed cycle gas turbine, the gas turbine exhaust is recycled to the compressor after being cooled and thereby forms a closed working fluid circuit, while in the open cycle the turbine exhaust is released to the environment, as shown in Figure 3.2. In addition, the heat is supplied to the closed cycle through a heat exchanger, instead of direct combustion of the fuel in the working fluid circuit as in the open cycle. The open cycle configuration is the most common configuration. Worldwide, only about 20 closed cycle gas turbines have been built. The perhaps most well-known closed cycle gas turbine plant is the Oberhausen II plant built in the former Federal Republic of Germany. This plant was commissioned in 1974 and used helium as working fluid.

Figure 3.2 Simple open cycle gas turbine and closed cycle gas turbine.
The advantages of the closed cycle gas turbine have been exemplified many times in literature, see for example McDonald (1985). The following is a summary of the most important advantages:

- **wide range of applications**
The closed cycle gas turbine is potentially applicable to a wide range of areas including electric power generation, marine propulsion, space power systems, underwater propulsion systems, and in terrestrial transportation systems such as buses and rail units.

- **adaptability to a wide range of heat source options**
The closed cycle gas turbine is capable of handling a wide range of heat source options. This includes dirty combustible fuels like coal, peat, wood, biomass, refuse etc. and also clean fossil fuels like oil and natural gas. Stored thermal energy and heat from chemical reactions and solar energy can also be utilized. Nuclear heat sources like fission reactors and radioisotopes have also been investigated. Future use of fusion reactors also represents a potential heat source.

- **no need for pressurized fuel**
Since there is no direct contact between fuel and the turbine working fluid, there is no need of pressurizing the fuel. This saves on compression work in the case of using a gaseous fuel. It also simplifies systems with solid fuels, since the complication of feeding a solid into a pressurized system is avoided.

- **operational fuel flexibility**
The closed cycle gas turbine is adaptable to a quick change of heat source if the fuel supply changes. It is also less sensitive to changes in the fuel quality.

- **freedom in working fluid selection**
The closed cycle gas turbine uses the same working fluid repeatedly and gases other than air can be used when their thermodynamic and transport properties are advantageous. Gases such as nitrogen, carbon dioxide, helium, argon, krypton, xenon and various gas mixtures have been suggested as suitable working fluids.

- **cleanliness of working fluid**
Since the working fluid is contained in a closed system, it can be kept free of moisture and contaminants including those arising from the combustion process. Theoretically, all dangers of fouling or eroding the blades of the compressors or turbines are eliminated. The possibilities of depositions on heat exchanger surfaces are likewise eliminated. Therefore, long life and unattended operation can be expected.

- **possibility of pressurization of the whole system**
With a closed cycle gas turbine, it is possible to pressurize the whole system. In this way, the required flow area within turbomachinery, ducts and heat exchangers can be minimized. Reduced equipment size can give lower capital cost and also give a lower weight and size to the system. High pressure also improves the heat transfer characteristic of the working fluid.

- **part-load operation with high efficiency**
With a pressurized closed system, it is possible to change the power output by changing the pressure level instead of reducing the turbine inlet temperature as in an open cycle gas turbine. The volume flow through the machine remains the same.
while the mass flow changes and this, in combination with a constant turbine inlet temperature, yields a good aerodynamic efficiency over a wide power range.

- containment of working fluid

In certain applications, a continuous rejection of the gas turbine working fluid to the atmosphere is undesirable for safety or environmental reasons. This is the case when the working fluid represents the primary cooling medium in a nuclear reactor and therefore may have been contaminated with radioactive material. Containment of the working fluid also enables the gas turbine to operation in environments where normal air-breathing machines can not be used due to the lack of gaseous atmosphere, like in space and in underwater applications.

Of course, these advantages of the closed cycle gas turbine system do not come without some offsetting costs. Selecting a closed cycle gas turbine for any particular application must be proven cost effective considering the following offsetting costs:

- heat source system including cycle high temperature heat exchanger
- components made structurally suitable for high system pressures and temperatures
- cycle heat rejection heat exchanger and system
- working fluid gas management system

Another disadvantage is the lower maximum allowable heat addition temperature of a closed cycle gas turbine compared to an open cycle gas turbine. The lower maximum temperature is a result of temperature limitations on the heat source heat exchanger. This limits the maximum power conversion efficiency of the closed cycle gas turbine.

### 3.3 Gas Turbine Fuels

Today the principal fuels burned in industrial gas turbines are natural gas, petroleum distillates, residual fuel oil, propane, blast furnace gas, and butane. Efforts to enable gas turbines to operate on solid fuels like coal and biomass are presently being undertaken. Other potential fuels to be used in gas turbines include methanol, hydrogen, and vegetable oil.

The development of coal and biomass gasification systems to produce a clean gas that can be directly combusted in a gas turbine combustor is an option being considered. This technology is applied in Integrated Gasification Combined Cycle (IGCC) systems. Gasification is also considered as an option for gas turbine based power generation from bagasse, an organic waste product from sugar manufacturing, or black liquor, a mixture of spent cooking chemicals and organic substances from the chemical pulp cooking process.

Another alternative for integrating solid fuel combustion in the gas turbine system is pressurized fluidized bed combustion, PFBC. Here, the gas turbine compressor supplies compressed air to a fluidized bed combustor. The hot combustion products are expanded in a turbine and the exhaust heat is recovered in a steam turbine bottoming cycle. The PFBC technology is mainly considered to be suitable for coal.

A third alternative is using an externally (or indirectly) fired gas turbine. In an externally fired gas turbine, combustion products never directly contact the gas
The Gas Turbine

turbine. Rather, the combustion products transfer heat through a high temperature heat exchanger to a working fluid, such as air, that drives the turbine. In this way the fuel cleaning requirements can be lessened.

The efficiency of all the above mentioned technologies with a gas turbine steam turbine combined cycle is estimated to reach 40% (LHV) with today's technology. Future projections show a potential of reaching an efficiency just exceeding 50%, (Hazard, 1985). Power generation using both closed and open externally fired gas turbines is the main topic in Chapter 5 of the thesis.

3.4 Environmental Performance

Upon comparison, gas turbines have very low pollutant emissions, particularly when operating with natural gas. Their high efficiencies especially when operating in combined cycle or in cogeneration mode make the emissions per unit of generated useable energy low. Implementing modifications to the combustion process can significantly reduce most of the air pollutants, such as NO\textsubscript{x}, CO and organic substances. Substantial efforts have been made to develop different emission reduction techniques, especially to develop low NO\textsubscript{x} gas turbines. Gasification of solid fuels provides for ways of removing pollutants like sulfur from the fuel gas before it is combusted. In pressurized fluidized bed combustion, a sorbent such as limestone or dolomite is used to capture sulfur released by the combustion. The externally fired gas turbine systems can be integrated with combustion systems that have low emissions, like atmospheric fluidized bed combustion systems.

The ways of eliminating CO\textsubscript{2} emissions from gas turbines is a new area of research. Here the studies have focused on two approaches: either enabling the gas turbine to operate on a CO\textsubscript{2}-neutral fuel like biomass, or using a fossil fuel and then capturing the CO\textsubscript{2} formed instead of venting it into the atmosphere.

3.4.1 CO\textsubscript{2} Capture from Gas Turbines

The goal of CO\textsubscript{2} separation and capture is to isolate CO\textsubscript{2} in concentrated form that enables efficient transport and storage. The carbon contained in the fuel can either be separated from the flue gas in a post-combustion approach or before the actual combustion process in a pre-combustion approach.

The post-combustion approach is suitable for old power plants since no changes are required for the power generation process. However, an alternate, more advanced post-combustion approach has been suggested, which increases the concentration of CO\textsubscript{2} in the flue gas through the use of oxygen for the combustion instead of using air. To maintain thermal conditions in the combustion zone and prevent overheating of the combustor liner materials, some of the flue gas would be recycled to the furnace, giving this approach the name "CO\textsubscript{2} recycle technology". Since the key to separating CO\textsubscript{2} from flue gas is to remove the CO\textsubscript{2} from the nitrogen, eliminating the air removes the primary source of nitrogen, which greatly simplifies the flue gas clean-up. However, an expense now arises from the production of the oxygen.

In pre-combustion separation, the hydrocarbon fuel is chemically shifted to obtain a fuel gas rich in H\textsubscript{2} and with the carbon in the form of CO\textsubscript{2}. This reduces the
size of the flow to be treated in the capture stage and increases the CO₂ concentration compared to the post-combustion approach.

The CO₂ in the exhaust or fuel stream has to be removed from the other stream constituents in the next stage of the process. With conventional methods, CO₂ can be absorbed from gas streams by contact with amine-based solvents or cold methanol. It can also be removed by adsorption on activated carbon or other materials or by passing the gas stream through special membranes. The pressure, temperature, other constituents present, concentration of CO₂ and the total volume to be treated determines which technology is best suited (IEA, 1993), (DOE, 1999). Several of these methods are commercially available. However, they have not yet been applied at the scale required for use as part of a CO₂ emissions mitigation strategy.

Historically, CO₂ capture processes have required significant amounts of energy, which reduces the power plant’s net power output and increases the cost of electricity. Table 3.1 shows typical penalties associated with CO₂ capture both as the technology exists today and how it is expected to evolve in the next 10-20 years, together with the estimated cost of electricity. Both the conventional coal and natural gas case use similar capture technologies, but because natural gas is less carbon intensive than coal, it has a lower energy penalty (Herzog et al., 1997).

To reduce the energy requirements and bring the cost of CO₂ capture to acceptable levels will most likely require a combination of the following:

- Increased base power plant efficiencies.
- Reduced capture process energy needs.
- Improved integration of the capture process with the power plant.

One novel method that combines all these requirements is Chemical Looping Combustion, CLC. It has been identified by US DOE as a method that could have a significant potential for combining power generation with fossil fuels and CO₂ separation (DOE, 1999). Chemical Looping Combustion is described in further detail in the following chapter.

Table 3.1 Typical energy penalties due to CO₂ capture using conventional techniques, and estimated cost of electricity (COE) (Herzog et al., 1997, Herzog and Vukmirovic, 1999). The energy penalty is defined as percent reduction in power output compared to the same plant without CO₂ capture.

<table>
<thead>
<tr>
<th>Power plant type</th>
<th>Energy Penalty Today</th>
<th>Energy Penalty Future</th>
<th>COE (S/MWh) Today</th>
<th>COE (S/MWh) Future</th>
<th>Incremental COE (S/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Coal, (Pulverized coal)</td>
<td>27-37%</td>
<td>15%</td>
<td>70-80</td>
<td>50-60</td>
<td>10-17</td>
</tr>
<tr>
<td>Natural Gas, NGCC</td>
<td>15-24%</td>
<td>10-11%</td>
<td>50-60</td>
<td>30-40</td>
<td>20-30</td>
</tr>
<tr>
<td>Advanced Coal, IGCC</td>
<td>13-17%</td>
<td>9%</td>
<td>60-70</td>
<td>40-50</td>
<td>20-30</td>
</tr>
</tbody>
</table>
4 Gas Turbine System with Chemical Looping Combustion

4.1 Introduction

In 1983, Horst Richter and Karl Friedrich Knoche introduced a new combustion process where the fuel is oxidized by an oxygen carrier, i.e. an oxygen-containing compound (Richter and Knoche, 1983). This combustion process was later given the name Chemical Looping Combustion (CLC). The main objective of introducing CLC at that time was to increase the energy conversion efficiency of thermal power plants by decreasing the combustion exergy loss. However, lately this process has gained attention as being a promising way of integrating combustion and CO₂ separation in power plants.

The research on CLC described in this thesis has been focused on system simulations of gas turbine based power generation with Chemical Looping Combustion. The main interest has been to study the exergy losses in the combustion system, while the CO₂ separation has been of secondary interest. Similar studies have been performed at Dartmouth College, USA (Harvey and Richter, 1994, Harvey, 1994), the Tokyo Institute of Technology, Japan (Ishida et al., 1987, 1997, Ishida and Jin, 1994a, Jin and Ishida, 1997). Bisio et al. (1998) repeated the calculations presented by Ishida and Jin (1994a). Results in the form of electric efficiency (\( \eta_e \), net electric power generated per fuel input) from these system simulations are summarized in Table 4.1. In 1995, Tokyo Electric Power Co., Inc. patented a Chemical Looping Combustion gas turbine system (US Pat. 5,447,024).

<table>
<thead>
<tr>
<th>Oxygen Carrier</th>
<th>Fuel</th>
<th>System</th>
<th>( \eta_e ) (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe₂O₃/FeO</td>
<td>CH₄</td>
<td>Fuel reforming GT (1100°C)</td>
<td>50%</td>
<td>Ishida et al., 1987</td>
</tr>
<tr>
<td>NiO/Ni</td>
<td>CH₄</td>
<td>GT (1200°C/1100°C)</td>
<td>55%</td>
<td>Ishida and Jin, 1994a</td>
</tr>
<tr>
<td>Fe₂O₃/Fe₂O₄</td>
<td>CH₄</td>
<td>Fuel reforming Fuel cell GT (1180°C)</td>
<td>69%</td>
<td>Harvey and Richter, 1994</td>
</tr>
<tr>
<td>NiO/Ni</td>
<td>Coal</td>
<td>Coal gasification Humid air GT (1200°C)</td>
<td>51%</td>
<td>Jin and Ishida, 1997</td>
</tr>
<tr>
<td>NiO/Ni</td>
<td>H₂</td>
<td>Humid air GT (1350°C)</td>
<td>67%</td>
<td>Ishida et al., 1997</td>
</tr>
</tbody>
</table>
Development of oxygen carriers and reactor systems has been performed at the Tokyo Institute of Technology (Ishida and Jin, 1994b, 1997, Ishida et al., 1996, 1998, 1999, Jin et al., 1998) and the National Institute for Resources and Environment (NIRE), Japan, (Hatanaka et al., 1997). In 1998 TDA Inc., USA, was awarded a research contract under US DOE's program for novel carbon sequestration techniques to investigate the potential of their “Sorbent Energy Transfer System, SETS” which seems identical to a Chemical Looping Combustion system with a combined cycle power generation system. The project is presently focusing on developing an oxygen carrier and a reactor system. Chalmers University of Technology, Sweden together with the Royal Institute of Technology has also been awarded research contracts to develop oxygen carriers and reactors and to perform system simulations. The Swedish projects are financed by the Environmental Section at Chalmers University of Technology and the University of Gothenburg, by the Swedish National Energy Administration under the program “Thermal Processes for Electricity Production”, and by Ångpanneföreningen (ÅF).

4.2 Description of Process

The fundamental differences between conventional combustion and Chemical Looping Combustion are demonstrated in this chapter. Two simple schematics of power generating systems with conventional combustion and Chemical Looping Combustion are given in Figures 4.1a and b.

In the conventional combustion process, the hydrocarbon fuel \( C_6H_6 \) and air enter the combustor. The fuel reacts with the oxygen, \( O_2 \), in the air and is oxidized to carbon dioxide, \( CO_2 \), and water, \( H_2O \), according to reaction (4.1) below, with a visible flame.

\[
C_6H_6 + \left( a + \frac{b}{4} \right) O_2 \rightarrow a CO_2 + \frac{b}{2} H_2O + \Delta H_c
\]  

(4.1)

This reaction is exothermic, i.e. heat equal to \( \Delta H_c \) is released. The heated excess air and combustion products leave the combustor.

In Chemical Looping Combustion, the overall combustion reaction takes place in two reaction steps in two separate reactors as shown in Figure 4.1b. In the so-called reduction reactor (Red), the fuel is oxidized by the oxygen carrier, i.e. the metal oxide \( MeO \).

Figure 4.1 a) System with conventional combustion.  
b) System with Chemical Looping Combustion.
The metal oxide is reduced to a metal or a metal oxide with a lower oxidation number, Me, in the reaction with the fuel, reaction (4.2). To regenerate the oxygen carrier, it is transported to the second reactor, the oxidation reactor (Ox), where it is reoxidized by oxygen in the air according to reaction (4.3). Both reactions proceed without a visible flame.

The net reaction over the two Chemical Looping Combustion reactors is equivalent to the conventional combustion reaction. This is verified by adding reaction (4.2) and (4.3) and observing that the sum is the conventional combustion reaction.

\[
\begin{align*}
\text{C}_2\text{H}_6 & + \left(2a + \frac{b}{2}\right) \text{MeO} + \Delta \text{H}_{\text{red}} \rightarrow \text{a CO}_2 + \left(\frac{b}{2}\right) \text{H}_2\text{O} + \left(2a + \frac{b}{2}\right) \text{Me} \\
+ & \left(2a + \frac{b}{2}\right) \text{Me} + \left(a + \frac{b}{4}\right) \text{O}_2 \rightarrow \left(2a + \frac{b}{2}\right) \text{MeO} + \Delta \text{H}_{\text{ox}} \\
\text{C}_x\text{H}_2 & + \left(a + \frac{b}{4}\right) \text{O}_2 \rightarrow \text{a CO}_2 + \frac{b}{2} \text{H}_2\text{O} + \Delta \text{H}_{\text{c}}
\end{align*}
\]

(4.2) \quad (4.3) \quad (4.4)

To confirm this conclusion, a control volume is drawn to enclose the two Chemical Looping Combustion reactors. It can then be seen that the same material is entering the CLC system, i.e. fuel and air and exiting, i.e. excess air and combustion products, as in the conventional combustor. The metal/metal oxide is circulated between the two CLC reactors and never leaves the system.

Chemical Looping Combustion is best suited for gaseous fuels like methane since the reaction rate has to be sufficiently high to allow the process equipment in continuous operation to be reasonable sized. Solid fuels like coal can be used if they are first gasified and then oxidized in the Chemical Looping Combustion system. The same procedure can be used for liquid fuels.

Metal oxides with metals from families VIIA and VIIIA of the periodic table, such as NiO, Fe\textsubscript{2}O\textsubscript{3} and Mn\textsubscript{3}O\textsubscript{4}, were initially suggested to be suitable as oxygen carriers from a thermodynamic point of view (Richter and Knoche, 1983, Harvey, 1991). The experimental work today is focused on using NiO or other Ni-based metal oxides (Tokyo Institute of Technology), different iron oxides (Chalmers), and iron- and copper-based oxides (TDA Inc.). The oxygen carrier is thought to be supplied to the system in the form of particles. The addition of inert materials to the particles is another area of research. Adding YSZ (Yttria Stabilized Zirconia), TiO\textsubscript{2} or Al\textsubscript{2}O\textsubscript{3} has been suggested by Ishida et al. (1998). The inert material plays the role of an oxide ion conductor to enhance the ion permeability in the solid. It also increases the particle’s porosity. Increased porosity increases the diffusion rate of reactants and products to and from the interior of the particle, which in turn leads to an increased overall reaction rate. The inert materials also improve the physical strength of the particles and prevent undesirable fragmentation.

Attempts have been made to suggest a suitable design for the oxidation and reduction reactors. Harvey and Richter (1994) suggest using two isothermal fluidized bed reactors with alternating valves. This allows the operation of a reactor to be switched from oxidation to reduction and vice versa without transporting the solids to another reactor. The oxidation reaction is run under atmospheric conditions while the
reduction reaction is pressurized. Notable is also that the heat requirements of the two reactors are exactly matched. Grönkvist (1995) tried to design and size the reactors for the system described in Paper I. Grönkvist found that the best type of reactor for the oxidation reaction is a fluidized bed reactor. For the endothermic reaction in the reduction reactor, a counter-current moving bed is considered the best choice since it is possible to achieve a high conversion of both phases in such a reactor. Mattisson and Lyngfelt (1999) suggest using a circulating fluidized bed reactor with an external fluidized bed reactor connected to the return leg, Figure 4.2. A high gas velocity that entrains the solid particles is used in the oxidation reactor. The gas and the solids are separated in a cyclone and the particles fall down through the return leg to the reduction reactor, a bubbling fluidized bed. Particle locks keep the gas streams from flowing from one reactor to the other.

4.3 CLC and Reduction of Combustion Exergy Destruction

Chemical Looping Combustion is one of several methods that are claimed to reduce combustion exergy losses. Exergy, also known as availability, is a measure of the maximum useful work that can be obtained when a system is brought to a state of equilibrium with the environment in a reversible process. Due to the irreversibility of thermal processes, the work obtained is always less than the maximum work. Hence, by analyzing the exergy flows within a system, imperfections can be pinpointed and quantified. Also, different sorts of energy can be directly compared in exegetic terms. For more detailed information about exergy analysis, see for instance Moran (1989) or Szargut et al. (1988).

The major loss of exergy in conventional thermal power plants occurs in the combustion process. Up to as much as 20-30% of the exergy content of the fuel can be destroyed. The high level chemical energy bound in the fuel is downgraded to low level thermal energy in the highly unordered and irreversible reaction between the
fuel and oxygen in the combustor. This energy degradation decreases the total efficiency whereby the fuel energy is finally converted to electricity in a thermal power plant (Dunbar and Lior, 1991). The exergy efficiency of the conventional combustion process increases with a decrease in excess air or an increase in air preheater temperature and pressure. The efficiency is also affected by the molecular structure of the fuel. The combustion exergy efficiency decreases with hydrocarbon chain length and increases with an increase in unsaturated bonds (Steward et al., 1998).

Beretta et al. (1992), suggested that preheating fuel and air at a certain pressure to a temperature corresponding to the temperature where the mixture exists in equilibrium, and then starting the reaction by cooling the mixture, would theoretically result in a reversible combustion. The exergy content of the fuel would then not be destroyed. However, for standard hydrocarbons, this reaction scheme would require extreme preheating or an extreme dilution of the hydrocarbon fuel. For the method to be practical, a suitable reaction scheme needs to be identified that allows for a lower equilibrium temperature which is suitable for current technology materials without having the fuel highly diluted.

Using fuel cells to convert the chemical energy directly into electricity is another way of improving the fuel energy utilization for simple fuels like hydrogen, H₂, and carbon monoxide, CO. In a fuel cell, oxidation of the fuel by direct reaction between fuel and air is prevented. The energy released is directly converted into an electric current, thus avoiding generation of large amounts of thermal energy. Fuel cells still suffer from some technical and economic drawbacks that have hindered a wider commercial application. Considerable resources are presently invested worldwide to further improve and develop fuel cells.

CLC has attracted interest as a method to decrease combustion exergy losses. This depends on the reaction path and thermodynamics of the two-step CLC reaction. The reactions are performed in a more ordered way than the conventional combustion reaction since direct contact between fuel and the combustion air is prevented. Instead the overall reaction takes place in two solid/gas phase reactions. The reaction between the fuel and the oxygen carrier MeO is usually endothermic, i.e. heat equal to ΔH_red is consumed. The reaction takes place at a medium-low temperature with recovery of heat at a medium temperature level. This heat can be taken from the exhaust of a gas turbine, for instance. The reoxidation of the oxygen carrier is exothermic, i.e. heat equal to ΔH_ox is released. According to Hess law or a simple energy balance, the sum of heat of reaction for reaction (4.2) and (4.3) is equal to the heat of combustion, ΔH_C. This means that the oxidation reaction, reaction (4.3), must have a higher heat of reaction than the conventional combustion reaction. As a result, more heat is released at a high temperature through recovery of thermal energy at a low temperature, compared to conventional combustion. The Chemical Looping Combustion system is thereby acting as a chemical heat pump system in upgrading the low-level energy to high-level energy. Therefore, the irreversible exergy destruction is thought to be less than in conventional combustion of the fuel, i.e. the exergy content of the released fuel energy should be better preserved. When this exergy is utilized efficiently in the subsequent power generation system, the overall thermal efficiency can be increased.
4.4 Environmental Performance of CLC - Separation of CO\textsubscript{2} and Suppression of NO\textsubscript{X}

One significant advantage in Chemical Looping Combustion is that the combustion products CO\textsubscript{2} and H\textsubscript{2}O leave the reduction reactor as a separate stream undiluted by excess air, Figure 4.1b. In this way it is easy to separate the greenhouse gas CO\textsubscript{2} to be stored or utilized in an environmentally safe way. All that is needed to get an almost pure CO\textsubscript{2} product is to condense the water vapor and remove the liquid water as shown in Figure 4.1b. This is to be compared to the costly and energy-demanding separation processes that are required for separating CO\textsubscript{2} from the mixed exhaust from the conventional combustor, as described in Chapter 3.4.1.

In addition, in the CLC combustion process, the fuel and air go through different reactors with no flame, which provide an opportunity to thoroughly suppress the generation of NO\textsubscript{X} (Ishida and Jin, 1996).

4.5 Objectives of CLC Study

The main objectives of the CLC study presented in Papers I-III have been the following:

- Model a gas turbine, (GT), based power generating system with CLC that can be constructed using existing conventional equipment to as large extent as possible. The CLC oxidation reaction temperature should be adapted to temperatures used in conventional gas turbines. The main objective of the system is to generate power at high efficiency.
- Investigate the possibilities of using the CLC GT system with different fuels.
- Compare CLC GT system with different metal oxides as oxygen carriers.
- Compare the performance of the CLC GT system with the performance of a similar GT system with conventional combustion.
- Perform an exergy analysis of the proposed CLC GT system and locate the points of exergy destruction. The CLC reactions are of particular interest. The results from the CLC GT system exergy analysis are to be compared with the results from an exergy analysis of the GT system with conventional combustion.
- Identify critical components and processes in the CLC system.

Aspen Plus, a program commonly used by engineers in the process and energy industries, has been used for the simulations. The program contains an array of predefined components, along with an extensive database of thermophysical properties. With the different system components and connectivity specified, energy and mass balances are computed sequentially until convergence is attained. The exergy of each stream is then computed using thermodynamic data from the Aspen Plus stream result-file.
4.6 Studies of CLC Power Generation Systems

4.6.1 CLC Gas Turbine System with Methane as a Fuel

The purpose of the investigation presented in Paper I and continued by Welin-Berger (1995) is to determine if it is possible to reach a high electric efficiency with a less complex CLC gas turbine configuration than the systems presented by Ishida et al., 1987 and Ishida and Jin, 1994a. Methane, CH₄ (the main component of natural gas) is used as a fuel and NiO or Fe₂O₃ is used as oxygen carrier. The performance of the CLC systems is compared to a gas turbine system with conventional combustion of the fuel. The detailed exergy analysis in Paper III reveals whether or not the combustion exergy loss is decreased by introducing Chemical Looping Combustion into the system as a replacement for conventional combustion.

4.6.1.1 System Description

The system introduced in Paper I is a Chemical Looping Combustion gas turbine system with reheat. Reheat denotes that the system has two combustors, one at the high pressure where the first combustion takes place with full combustion of the fuel and then a second combustor at an intermediate pressure where additional fuel is supplied and fully combusted. Design data used for the gas turbine system is taken from a state-of-the-art gas turbine, in this case the ABB's gas turbines GT24/26. Following the specifications for GT24/26, the maximum turbine inlet temperature is set to 1235°C and the maximum pressure is set to 30 bars for GT system 1 with air as the working fluid. Turbines for expanding the gases from the reduction reactors are added to increase the power production.

Nickel oxide, NiO, is used as an oxygen carrier in the study in Paper I, Figure 4.3. The NiO particles are reduced to Ni by the fuel. The reactors are pressurized to allow a direct connection with the gas turbine system.

![Figure 4.3 CLC gas turbine system with NiO as oxygen carrier and methane as a fuel.](image-url)
The compressed air is introduced to the oxidation reactors where it reacts with Ni according to reaction (4.5).

4 Ni + 2 O₂ → 4 NiO (4.5)

This reaction is exothermic and the temperature of the outgoing excess air and NiO is raised to 1235°C. The conversion of Ni to NiO is assumed to be 100%. The reactor is modeled as a fluidized bed reactor. In the reduction reactors, NiO is reduced by methane to Ni according to reaction (4.6).

CH₄ + 4 NiO → CO₂ + 2 H₂O + 4 Ni (4.6)

Again the conversion of NiO and CH₄ is assumed to be 100%. This reaction is endothermic, i.e. heat from the reactant NiO and heat transferred from the excess air in the heat exchanger are consumed. The reduction reactor is thought to be either a fluidized bed or a moving bed reactor with a reactor outlet temperature of 435°C. The pressure of the methane introduced into loop A is 30 bars and into loop B is 15 bars. Both exhausts from the oxidation reactor and the reduction reactor are expanded through gas turbines, GT2 A and B, to generate power.

Changes were later made to the original ASPEN PLUS input file by replacing the original oxygen carrier NiO with hematite, Fe₂O₃ (Welin-Berger, 1995). Two reaction schemes with Fe₂O₃ were examined. In the first scheme, the fuel reduces the hematite particles to magnetite, Fe₃O₄, according to reaction (4.7):

CH₄ + 12 Fe₂O₃ → CO₂ + 2 H₂O + 8 Fe₃O₄ (4.7)

The reaction in the oxidation reactor is an oxidation of magnetite with oxygen.

8 Fe₃O₄ + 2 O₂ → 12 Fe₂O₃ (4.8)

However, this system was later abandoned due to the temperature limitations imposed by the reactions and the resulting complicated process layout. In addition, the electric efficiency of this system was found to be low. Instead, it was determined to use a system where the oxygen carrier Fe₂O₃ is reduced to wustite, FeO.

CH₄ + 4 Fe₂O₃ → CO₂ + 2 H₂O + 8 FeO (4.9)

In the oxidation reactor the wustite is reoxidized to hematite:

8 FeO + 2 O₂ → 4 Fe₂O₃ (4.10)

Equilibrium calculations show that the maximum temperature allowed in the oxidation reactors is 1197°C and 1179°C for reactor A and B respectively. At higher temperatures Fe₂O₃ is unstable and converts to Fe₃O₄. Equilibrium calculations also reveal that the temperature in the reduction reactors has to be above 400°C for reaction (4.9) to take place. The original CLC system configuration is therefore changed, allowing some of the heat remaining in exhaust 2 to be transferred to the
reduction reactors. However, this additional heat transfer is not enough to raise the minimum reaction temperature to 400°C. Therefore, an inert component, ZrO₂ (1.15 kmole/kmole Fe₂O₃), has been added to the two loop subsystems to transfer enough heat from the oxidation reactor to the reduction reactor. ZrO₂ was chosen as the heat carrier since ZrO₂ stabilized by yttria (YSZ) has been used in some CLC experiments with acceptable results (Ishida et al., 1996).

4.6.1.2 Results

The performance of the two CLC systems is compared with the performance of a similar reheat GT system using conventional combustion. In Table 4.2, the performances of the systems are compared on the basis of their electric efficiencies, \( \eta_e \). As shown, there is a significant improvement in electric efficiency for the two gas turbine systems with CLC over the system with conventional combustion. Of the two CLC systems, the system with Fe₂O₃ as oxygen carrier has the highest electric efficiency.

In this comparison, it is important to remember that the results are for power generation systems only containing gas turbines. The temperatures of the exhaust streams are high enough for additional power to be generated in a gas turbine bottoming cycle using the exhaust streams as the heat source. The potential of power generation in a bottoming cycle is estimated by calculating the physical exergy given up by the exhaust when cooled to 100°C. By definition, this value represents the theoretical maximum power that can be generated in a bottoming cycle using the exhaust heat down to a temperature of 100°C. However, due to external and internal

<table>
<thead>
<tr>
<th>Table 4.2 Electric efficiency for gas turbine systems with methane as fuel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT Electric Efficiency (% LHV)</td>
</tr>
<tr>
<td>CLC with NiO/Ni</td>
</tr>
<tr>
<td>CLC with Fe₂O₃/FeO</td>
</tr>
<tr>
<td>Conventional Combustion</td>
</tr>
</tbody>
</table>

Figure 4.4 Total electric efficiency vs. bottoming cycle exergy efficiency.
irreversibilities in a real bottoming cycle, the physical exergy in the exhaust can not fully be converted to power. To be able to estimate a realistic total efficiency of a combined cycle with CLC or conventional combustion, only a part of the physical exergy is assumed to be converted into power in the bottoming cycle. Figure 4.4 shows the total electric efficiency as a function of the percentage of the physical exergy converted into power. The exergy efficiency of a conventional bottoming steam cycle, defined this way, is around 40-70%, depending on the number of pressure levels and steam data. Figure 4.4 reveals that in this exergy efficiency range, the electrical efficiency for the CLC combined cycle systems is 53-60%, which is slightly higher than for the system using conventional combustion. The difference in efficiency between the system using NiO and Fe$_2$O$_3$ as an oxygen carrier in the same exergy efficiency range is small. Therefore, for a combined cycle configuration no oxygen carrier seems better than the others based on electric efficiency.

Looking at the total amount of solid material in the two loops per unit of power generated, Table 4.3, NiO seems to be more practical as an oxygen carrier, since this system has a lower flow rate of solids per MW power generated. A lower mass flow rate per unit of power is advantageous in that the additional power requirements for transportation of the solids in the loop are likely to be lower. A low volume flow rate per unit of power is beneficial in that the size and thereby the capital cost of the loop process equipment can be kept low. This indicates that NiO would be a better choice as an oxygen carrier. It is therefore concluded that NiO seems to be the better alternative of the two oxygen carriers considered, and the rest of the analyses are consequently only for NiO as the oxygen carrier.

In Paper III, a detailed exergy analysis of the CLC gas turbine system with NiO as an oxygen carrier and the gas turbine system with conventional combustion is presented. The Grassmann Diagrams in Figure 4.5 reveal the magnitude and location of exergy destruction in these systems. In Table 4.4 the total exergy destruction in the different subsystems is presented. The exergy destruction is less in the CLC reaction system than in the conventional combustion. The total exergy destruction including power generation is less using the CLC system than using the conventional system.

Table 4.3 Theoretical flow rates of solid per MW power produced. The solid mass and volume flow rates are based on NiO and Fe$_2$O$_3$ + ZrO$_2$, respectively (Anheden, 1997). The volume flow does not include particle pores and bed voids.

<table>
<thead>
<tr>
<th></th>
<th>Solid Power Density</th>
<th>Solid Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>((kg/s)/MW$_p$)</td>
<td>((cm$^3$/s)/MW$_p$)</td>
</tr>
<tr>
<td>CLC with NiO</td>
<td>0.84</td>
<td>123</td>
</tr>
<tr>
<td>CLC with Fe$_2$O$_3$</td>
<td>3.28</td>
<td>659</td>
</tr>
</tbody>
</table>
Figure 4.5 Grassman diagrams. Exergy expressed as percentage of fuel chemical exergy. a) Chemical Looping Combustion GT system. b) GT system with conventional combustion.
Table 4.4 Exergy destruction expressed as a percentage of fuel chemical exergy. Reaction subsystem includes oxidation and reduction reactors and heat exchangers A and B and the two combustors for the conventional combustion system. The power generation system includes compressors and turbines.

<table>
<thead>
<tr>
<th></th>
<th>Exergy Destruction</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reaction subsystem</td>
<td>GT System</td>
<td>Total Reaction +</td>
</tr>
<tr>
<td></td>
<td>(% fuel ch. ex.)</td>
<td>(% fuel ch. ex.)</td>
<td>GT system</td>
</tr>
<tr>
<td>CLC NiO/Ni</td>
<td>22.7</td>
<td>8.4</td>
<td>31.1</td>
</tr>
<tr>
<td>Conventional Comb.</td>
<td>26.2</td>
<td>7.1</td>
<td>33.4</td>
</tr>
</tbody>
</table>

4.6.2 CLC System with Gasified Coal as a Fuel

The main objective of the investigation presented in Paper II was to determine whether or not it is possible to make changes to a CLC system in order to use coal as a fuel and still maintain a high efficiency. As stated in Chapter 2, coal fired power plants account for a large part of power generation today and it is projected that coal will continue to be the dominating fuel in the future. Coal fired power plants also contribute greatly to the emissions of CO₂. Integrating the CLC system with a coal fired power plant, provides an efficient way to separate the CO₂ from other combustion products and excess air. Paper III presents a detailed exergy analysis of the systems proposed in Paper II.

4.6.2.1 System Description

Direct reaction between the coal and the oxygen carrier in the CLC system was not expected to be feasible, since the reaction rate is likely to be too slow. There is a risk of coal and ash covering the metal particle surface and thereby hindering the Chemical Looping Combustion reactions. It is also likely that a large part of the coal fed to the reduction reactor will be entrained with the metal stream and combusted with oxygen in the air in the oxidation reactor, instead of reacting with the oxygen carrier in the reduction reactor. Thus the advantage of easy CO₂ separation is lost. To create an acceptable reaction scheme, the coal is instead first gasified and then the resulting syngas is fed to the CLC reduction reactor where it is oxidized. A simplified schematic of the simulated system is found in Figure 4.6.

A pressurized oxygen-blown gasifier is chosen for achieving low dilution of the resulting syngas. An undiluted syngas makes it possible to get a high concentration of CO₂ and H₂O in the gaseous products from the CLC reduction reactor and, therefore, enables an easier separation of carbon dioxide. However, this requires integration into the system of an air separation unit for separating oxygen from the other components of the air, mainly nitrogen. This increases the investment and operation cost of the power plant.

The CLC GT system consists of a single CLC loop where the two exhausts are expanded in separate turbines. The maximum turbine inlet temperature is set to
Figure 4.6 Schematic process layout for CLC gas turbine combined cycle system with coal as fuel.

1280°C and turbine inlet pressure 17 bars; data likely to be used in future industrial gas turbines.

Three different oxygen carriers are tested, NiO, Fe₂O₃ and Mn₃O₄. The reaction schemes are as follows:

\[
\begin{align*}
\text{Ni} + 0.5 \text{O}_2 & \rightarrow \text{NiO} \quad (4.11) \\
0.63 \text{CO} + 0.36 \text{H}_2 + 0.0004 \text{CH}_4 + \text{NiO} & \rightarrow 0.63 \text{CO}_2 + 0.37 \text{H}_2\text{O} + \text{Ni} \quad (4.12) \\
2 \text{FeO} + 0.5 \text{O}_2 & \rightarrow \text{Fe}_2\text{O}_3 \quad (4.13) \\
0.63 \text{CO} + 0.36 \text{H}_2 + 0.0004 \text{CH}_4 + \text{Fe}_2\text{O}_3 & \rightarrow 0.63 \text{CO}_2 + 0.37 \text{H}_2\text{O} + 2 \text{FeO} \quad (4.14) \\
3 \text{MnO} + 0.5 \text{O}_2 & \rightarrow \text{Mn}_3\text{O}_4 \quad (4.15) \\
0.63 \text{CO} + 0.36 \text{H}_2 + 0.0004 \text{CH}_4 + \text{Mn}_3\text{O}_4 & \rightarrow 0.63 \text{CO}_2 + 0.37 \text{H}_2\text{O} + 3 \text{MnO} \quad (4.16)
\end{align*}
\]

It is assumed that all reactions undergo 100% conversion of the fuel and oxygen carrier. These assumptions are verified through equilibrium composition calculations.

The basic CLC-loop layout used is the same as in Figure 4.3, however, some modifications were necessary due to differences in the heat of reaction depending upon which oxygen carrier is chosen and the fuel composition, Paper II. Unlike the other CLC systems presented, the reaction in the reduction reactor using Mn₃O₄ as the oxygen carrier is exothermic, reaction (4.16). The reactor is cooled by recirculating CO₂ from the separation condenser to prevent the temperature from exceeding the maximum temperature of 1280°C. The oxidation reaction, (4.15), also proceed with an adiabatic temperature of 1280°C.

To increase the overall power efficiency, the heat remaining in the CLC gas turbine system exhausts is used to generate steam in a heat recovery steam generator (HRSG) connected to a steam bottoming cycle. If CO₂ separation is desirable, the water vapor in the reduction reactor exhaust stream is condensed. The gaseous product, consisting mostly of CO₂, can then be separated and disposed of in an environmentally safe way.
4.6.2.2 Results

The main results from the simulations of the CLC GT systems using coal as a fuel are presented in Table 4.5 and Figure 4.7. The results are based on a flow rate of 15 kg coal/s into the gasifier, (LHV = 25 MJ/kg). The performance of the CLC gas turbine combined cycle systems are compared to a gas turbine combined cycle system where the syngas is combusted in a conventional way. The potential of generating additional power in a bottoming cycle has been estimated by calculating the physical exergy given up by the CLC system exhaust streams when cooling to 100°C in the HRSG. The exergy of the heat removed in the syngas cooler in the gasification system has also been included.

First of all, comparing the net power output from the gas turbines in the CLC and conventional combustion systems, it is found that the CLC NiO and MnO₃ systems and conventional combustion system have power outputs in the same range. The CLC Fe₂O₃ system has a 9% higher output than the conventional system. When the potential of generating power in a bottoming steam turbine system is included, it is found that the CLC NiO and MnO₃ and the conventional combustion system have outputs in the same range, while the CLC Fe₂O₃ system has a somewhat lower maximum output. The differences in power output diminish, as seen in Figure 4.7.

Table 4.5 Results from simulations of CLC and conventional combustion systems with coal as fuel. \( \dot{W}_{\text{net,GT}} \) stands for the total net power generated in the CLC gas turbine system minus the power consumed in the ASU, Paper II.

<table>
<thead>
<tr>
<th>CLC System</th>
<th>( \dot{W}_{\text{net,GT}} ) (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLC NiO</td>
<td>120</td>
</tr>
<tr>
<td>CLC Fe₂O₃</td>
<td>132</td>
</tr>
<tr>
<td>CLC MnO₃</td>
<td>118</td>
</tr>
<tr>
<td>Conventional</td>
<td>121</td>
</tr>
</tbody>
</table>

Figure 4.7 Total net power generated by gas turbine and steam turbine systems as a function of the exergy efficiency of the bottoming steam turbine system, Paper II.
Table 4.6 Exergy losses in the reaction subsystem (oxidation and reduction reactor, heat exchanger alt. combustor) and power generation system (compressor of air to combustor or oxidation reactor plus gas turbines). Losses expressed as a percentage of the syngas chemical exergy at environmental temperature and pressure.

<table>
<thead>
<tr>
<th></th>
<th>Exergy Destruction</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reaction Subsystem</td>
<td>GT System</td>
<td>Total Reaction</td>
</tr>
<tr>
<td></td>
<td>(% fuel ch. ex.)</td>
<td>(% fuel ch. ex.)</td>
<td>(% fuel ch. ex.)</td>
</tr>
<tr>
<td>CLC NiO</td>
<td>19.98</td>
<td>6.73</td>
<td>26.71</td>
</tr>
<tr>
<td>CLC Fe₂O₃</td>
<td>20.07</td>
<td>8.79</td>
<td>28.87</td>
</tr>
<tr>
<td>CLC Mn₃O₄</td>
<td>20.02</td>
<td>6.40</td>
<td>26.42</td>
</tr>
<tr>
<td>Conventional</td>
<td>22.88</td>
<td>6.51</td>
<td>29.38</td>
</tr>
</tbody>
</table>

when the exergy efficiency of which the physical exergy can be converted into power in the steam turbine system is accounted for. In the range 60-67% exergy efficiency, which is a reasonable exergy efficiency for the bottoming cycle defined this way, all four systems have similar power output.

A detailed analysis of the exergy destruction in the CLC gas turbine systems with NiO and Fe₂O₃ is presented in paper III and with Mn₃O₄ in Anheden (1997). The resulting Grassmann Diagrams are found in these publications. In Table 4.6, the total loss of exergy in the reaction subsystem and power generation subsystem is computed, along with the total loss of exergy in the CLC GT system.

The losses caused by the reactions are significantly lower in all the CLC reaction systems compared to the conventional combustion. If power generation is included in the analysis, the Fe₂O₃ system is found to have higher exergy destruction in the gas turbines than the others, due to the high flow rate of air. Totally, the exergy destruction is lowest in the Mn₃O₄ CLC GT system followed by the NiO system. The Fe₂O₃ system has a somewhat higher total exergy destruction and the system with conventional combustion has the highest total exergy destruction of the systems considered.

Simulation results also show that the mass and volume flow of solids in the NiO CLC system was significantly less than in the CLC systems with Fe₂O₃ or Mn₃O₄ as the oxygen carriers.

4.7 Discussion of Results and Conclusions

The present investigation explores the thermodynamics of simple gas turbine cycle systems and combined cycle systems with Chemical Looping Combustion. The effect of using NiO, Fe₂O₃ and Mn₃O₄ as oxygen carriers is investigated.

It has been generally observed that the combustion exergy destruction and the total exergy destruction in the CLC gas turbine systems are less when using NiO, Fe₂O₃ or Mn₃O₄ as oxygen carrier than the destruction observed in a gas turbine system with conventional combustion of the fuel. The electric efficiency for the CLC simple gas turbine system is in some cases higher than for a gas turbine system with
conventional combustion. In these cases, heat from the GT exhaust has been recovered in the reduction reactor.

In a combined cycle application, the systems with CLC and conventional combustion have similar electric efficiencies, with a small potential advantage for the CLC systems. This indicates that there is only a minor thermodynamic advantage of using CLC in a combined cycle configuration. There are two main reasons why a major advantage for CLC in a combined cycle system is not observed. First, a part of the exergy saved in the CLC process is in the form of a difference in concentration between the constituents of exhaust streams and the environment. This exergy cannot be utilized for thermal power generation. Secondly, due to the increased heat of reaction of the oxidation reaction relative to the conventional combustion reaction, a higher flow rate of air is necessary to limit the temperature of the gaseous product stream to the maximum allowable turbine inlet temperature. This increased flow rate of air increases the loss of exergy with the exhaust stream leaving the HRSG at 100°C. In the case of Mn₃O₇ as an oxygen carrier, the last observation does not hold, since the oxidation reaction is less exothermic than the conventional combustion reaction. The air flow rate is then lower than in the conventional combustion process. However, the higher inert gas flow rate for cooling the reduction reactor increases the exergy lost to the environment with the gaseous reduction reaction exhaust stream instead.

The main advantage of CLC is considered to be connected to the integration of CO₂ separation into the combustion process. When including CO₂ separation, it is likely that the CLC systems would have a lower energy penalty and a higher electric efficiency than a comparable system with conventional combustion combined with separation of CO₂. Theoretically, the only penalty connected to CO₂ separation in the CLC process is the compression of CO₂. This is only a very small part of the energy penalty for conventional power plants with CO₂ separation reported in Table 3.1.

Of the oxygen carriers studied, NiO seems preferable. However, more experimental data is needed before a definite decision can be made in choosing the optimal oxygen carrier. The performance of the plant using NiO as an oxygen carrier is satisfactory. The mass- and volume flow rates of the Ni oxygen carrier in its two oxidation forms are significantly lower than for the other oxygen carriers. Another advantage of Ni is that it has fewer oxide forms than Fe and is therefore less sensitive to changes in, for instance, temperature, excess air and pollutants that might alter the reaction path. Reactivity tests performed at Tokyo Institute of Technology also showed a higher reaction rate and degree of conversion for Ni than for Fe. It was also shown that particles of Fe₂O₃ had a tendency to crack after repeated cycles of oxidation and reduction, (Ishida and Jin, 1994b and 1997). As a consequence there is a risk of dust formation. This is undesirable since it can cause loss of oxygen carrier in the loop and in addition, the turbine is also very sensitive to solid particles in the expanding gas stream. On the other hand, Ni is more expensive and has a more negative effect on the environment than Fe. The lack of experimental data in the case of Mn as an oxygen carrier makes it difficult to evaluate this option. However, no major thermodynamic advantage can be seen in using Mn.

Another area that should be addressed is the addition of inert material to the oxygen carrier. Even though the addition of this material has positive effects on the
Gas Turbine System with Chemical Looping Combustion

reaction rate, the performance of the GT system is decreased. This is due to the transportation of sensible heat from the oxidation reactor to the reduction reactor with the inert material. This in turn decreases the possibilities of exhaust heat recovery in the reduction reactor and thereby decreases GT cycle performance, as shown in Figure 7, Paper I. The same effect is seen if the oxidation conversion efficiency of the oxygen carrier is less than 100%. A difference in thermodynamic performance of the CLC system is noticed depending on fuel composition used. Using CH₄ as a fuel improves the exhaust heat recovery compared to using syngas. The reason for this is that the reaction between the oxygen carrier and the syngas is less endothermic and, therefore, less exhaust heat can be recovered in the reduction reactor.

4.7.1 Identification of Critical Issues and Suggestions for Future Work

During the modeling of the CLC systems, a number of assumptions have been made regarding the CLC systems' performance. It is necessary to collect more experimental data under realistic conditions to be able to check the validity of these assumptions. The simulation models can then be used to predict the full potential of integrating Chemical Looping Combustion in a power generation system more accurately. Among the critical operating parameters are reactor operating temperature, reaction kinetics, reaction conversion efficiency, reaction products and induced pressure drops. The properties of the particle such as mechanical strength, porosity etc. are also of importance. Design of process equipment is another issue that need careful considerations. Finally, optimization of the power generation system from both a thermodynamic and economic perspective including the special implications connected to separation of CO₂ is necessary.

The operating temperature of the reactors and the induced pressure drops are two of the critical operating parameters that directly affect the electric efficiency. The temperature in the oxidation reactor determines the turbine inlet temperature, while the temperature of the reduction reactor controls the temperature level of the recoverable exhaust heat. The operating temperature is, above all, dependent on which oxygen carrier is chosen. The temperature is limited by the melting or vaporization point of the solid constituents and the desired reaction products, reaction rates and degree of conversion. The pressure drop is primarily dependent on reactor configuration and the amount of solid material in the reactors.

The degree of conversion of the fuel in the reduction reactor is another important concern. If full conversion can not be realistically achieved, a way of separating and recycling the unreacted fuel or some other way of utilizing the energy content of the fuel has to be found.

One of the most important issues deals with choosing an oxygen carrier. The study presented in this thesis has focused on the thermodynamic effects of different oxygen carriers. There are still other issues that need more thorough investigation. An oxygen carrier that has a sufficient rate of reaction for both the oxidation and reduction reaction needs to be found. Any side reactions, for instance carbon formation, that may occur need to be identified and avoided. Reactions leading to a
deactivation of the oxygen carrier also have to be identified. If deactivation can not be completely avoided, an oxygen carrier regeneration process might be necessary. The rate of sintering, agglomeration, and fragmentation of the solid material needs to be investigated so that these rates can be kept to a minimum. Another issue to be addressed is whether to use an inert material or not since the reactivity and strength of the solid material is greatly affected by the material used. The inert material's cost and possible side reactions are also important. For instance, Ishida and Jin (1997) showed that carbon deposition from the fuel on solid particles of NiO/YSZ was related to the zirconium-content of the particle. The size and structure of the particles are also expected to have a significant influence on the reactivity, since the reaction rate is thought to be limited by transportation of reactants and products to and from the particle interior. Suitable particle manufacturing methods that give a highly reactive particle suited for cyclic use in a CLC system need to be developed.

Most of the issues mentioned can only be resolved through experimental work under realistic operating conditions. Therefore, one of the key issues to continue this work on CLC is to perform experiments. However, computer simulations can still be used to give information on the effect of certain design parameters on system performance and help in identifying desirable operating conditions.

Careful design of the equipment required for CLC is needed. The pressure drop over the reactors needs to be low since this directly affects the performance of the power generation system. Development of high temperature filters that minimizes the emission of dust from the oxygen carrier is another important design problem. Experience with this type of filter can probably be collected from the development of filters for PFBC and IGCC plants.

Continued power generation system design and optimization and simulations concentrating on the implications associated with CO₂ separation are required. If the primary objective for using CLC is for its CO₂ separation capability, a slightly different plant configuration than the one described in this thesis might be preferable, since the CO₂ is to be delivered at a high pressure (about 74 bars) for efficient transportation and storage. By opting not to expand the exhaust from the reduction reactor, the CO₂ leaves the system at a high pressure. The heat remaining in the exhaust could be utilized in the bottoming cycle. This scheme saves some power for CO₂ compression and possibly increase the overall electric power conversion efficiency from fuel to CO₂-disposal. TDA Inc. has estimated an energy penalty of about 5% for a similar configuration (DOE Fossil Energy, 1999).

Alternate ways of improving the gas turbine system's performance should also be investigated, concentrating on heat recovery. Studies have, for instance, shown that using a gas turbine system with humidification of the air and the fuel has a positive influence both on the power conversion efficiency through improved heat recovery and decreases the rate of carburization of the oxygen carrier (Ishida and Jin, 1994a, Bisio et al., 1998, Ishida and Jin, 1997, Ishida et. al, 1998).
5 Closed and Open Externally Fired Gas Turbines for Power Generation from Biomass Fuels

5.1 Introduction

There are a number of thermal power technologies, both existing and under development, which can be employed with a solid fuel like biomass. Most of the existing biomass fired plants involve a steam-Rankine cycle; but in terms of thermodynamic performance, cycles featuring gas turbines offer the greatest potential for high efficiencies compared to conventional steam-Rankine systems. The integrated gasification combined cycle (IGCC) is probably the most well known emerging technology for integrating solid biomass fuels with gas turbines. However, a number of serious technical obstacles remain with IGCC, mostly related to gas cleanup (i.e., elimination of particulates and reduction of alkali levels). As an alternative to both steam-Rankine and IGCC technologies, externally fired gas turbine (EFGT) systems offer a number of advantages. For instance, since the gas turbine is indirectly fired, EFGT systems are capable of utilizing a variety of furnace types and pollution controls, including many of the well-proven technologies featured in steam-based systems. Aside from higher efficiencies, EFGT systems have an advantage over steam-Rankine systems in that operating pressures are reduced (<40 bar) and feed water treatment is not needed. Because the gas turbine in a EFGT cycle utilizes a clean working fluid, contamination of sensitive turbomachinery components is much less of an issue as compared to IGCC.

Studies of externally fired gas turbines have been performed by a number of different research organizations and power equipment manufacturers. The main part of the research has been considering coal as the fuel, but lately, the use of biomass fuels has been gaining increased attention. This investigation has focused on exploring the use of EFGT cycles for biomass-fueled, small-scale cogeneration. A thermodynamic and economic performance analysis is presented for both open and closed EFGT cycle configurations.

A number of externally fired gas turbines were built in Western Europe during the 1930's to 1960's. They were fueled with dirty fuels like coal, mine gas, blast furnace gas etc. The gas turbines were built with a closed working fluid circuit and the leading manufacturer was Escher Wyss AG, Switzerland. About 20 closed cycle gas turbines were built during this period. As the supply of cheap clean fuels like natural gas and oil, suitable for direct combustion in the gas turbine, increased and the trend for gas turbine inlet temperature increased, the interest in externally fired closed cycle gas turbines faded. However, in the mid-1970s, as the decreased
availability and subsequent increase in cost of clean fossil fuels were forecast to lead to an increased use of coal, various development activities of externally fired gas turbines were initiated in the United States. During this time, closed cycle gas turbines were also considered for power generation in high temperature gas cooled nuclear reactors. Paper IV summarizes the development and operating experience on closed cycle gas turbines together with equipment considerations. Information on closed cycle gas turbines can also be found in McDonald (1985) and Pietsch (1985).

US Department of Energy, DOE, has in recent years supported development programs for open externally fired gas turbines, including the Externally Fired Combined Cycle (EFCC) development program initiated in 1987. In addition, the related Combustion 2000 program, together with the High Performance Power System, (HIPPS) program were initiated in 1992. The companies that are or have been involved in different stages of the system and equipment studies are Foster Wheeler, United Technologies, Hague International Stone & Webster, Allison and Westinghouse. In Europe, Ansaldo, ENEL (the Italian national utility) and research institutions have been engaged in prospective studies of externally fired gas turbines since 1992 with funding from the European Union (Consonni et al., 1996). The Netherlands Agency for Energy and Environment has included EFCC in its New Energy Conversion Technologies Program (Korobitsyn, 1998). In Belgium, the TERMIE program of the European Commission and the VLIET program of the Flemish Government support a demonstration project of a combined heat and power (CHP) externally fired gas turbine plant. The plant is fueled by the product gas from a biomass gasifier (Marroyen et al., 1999). In Sweden, the Swedish National Board for Industrial and Technical Development (NUTEK) and later the Swedish National Energy Administration (STEM) support studies of biomass fueled externally fired gas turbines. The studies include both EFCCs and evaporative externally fired gas turbine cycles (Yan et al., 1994, Eidensten et al., 1996) as well as the study of small scale open and closed externally fired gas turbine systems presented in Papers V-VII. Yan (1998) and Korobitsyn (1998), have compiled summaries of the worldwide research on open EFGT cycles, together with a review of the predicted performance of the different configurations.

5.2 Principal Description of Externally Fired Gas Turbines

Figure 5.1 shows the directly fired gas turbine and the externally fired gas turbine. The externally fired gas turbine is different from the directly fired gas turbine in that the combustion process takes place outside the working fluid circuit. This has the following implications:

- The combustion process takes place at atmospheric pressure.
- A high temperature heat exchanger is required to transfer heat to the gas turbine working fluid.
- Clean air is expanded through the turbine.
Because of this, it is possible to use a solid fuel without the complication of how to feed it into a pressurized system. The demands on the quality of the combustion products (contents of solids, tars, corrosive components etc.), are decreased since the heat exchanger is less sensitive than the turbine. Low quality gaseous and solid fuels can then be used without complicated clean-up equipment. There are two different basic configurations of the externally fired gas turbine, Figure 5.1a; the open cycle configuration and the closed cycle configuration as described in Chapter 3.2.

The challenge for the externally fired cycle is to develop a high temperature heat exchanger (HTHx) that is capable of supplying a high turbine inlet temperature, in addition to withstanding the stresses imposed by the working conditions and the constituents in the combustion gases. Two important issues to consider for using high temperature heat exchangers are the size and cost of these units. The maximum allowable temperature is dependent on the furnace and heat exchanger material, configuration and the quality of the fuel, especially its ash chemistry. As a general rule, nickel-based super alloys allow turbine inlet temperatures to reach 800-825°C. More advanced oxide dispersion (ODS) alloys can withstand temperatures of approximately 950°C up to 1100°C. A ceramic heat exchanger made from silicon carbide composites is capable of operating at levels of 1000°C and is expected to allow levels of 1370°C in the future. In the open externally fired gas turbine cycle, additional clean gaseous fuel can be combusted in a topping combustor located behind the high temperature heat exchanger, so called top-firing. This configuration increases the turbine inlet temperature and thereby the thermal efficiency. The high temperature heat exchanger designs that have been suggested include different types of gas-gas heat exchangers or fluidized bed heat exchangers. More information about high temperature heat exchanger materials and design is compiled in Paper IV, Yan (1998), and Korobitsyn (1998).

5.3 Objectives of EFGT Study

The main objectives of the study on the closed and open externally fired gas turbines presented in Papers IV-VII have been to:
Analysis of Gas Turbine Systems for Sustainable Energy Conversion

- Summarize previous research and operating experience on closed cycle gas turbines.
- Drawing on the conclusions from this review, suggest a closed externally fired gas turbine configuration suitable for the Swedish energy system and calculate its performance for a specified application.
- Examine the effects of using different working fluids in closed cycle gas turbines.
- Compare the performance of open and closed externally fired gas turbines.
- Investigate the economic feasibility of the suggested systems.
- Compare the thermodynamic and economic results from the EFGT study with the thermodynamic and economic performance of present and emerging competing technologies.

The thermodynamic performance of the studied systems was calculated using the process simulation software Aspen Plus. The performance of the individual system components was estimated using state-of-the-art component efficiencies as reported in Papers V-VII. Equipment size estimates were made using known correlations. The equipment cost of the plants was estimated based on quotas from equipment manufacturers and other reliable sources.

5.4 Study of EFGT for Small-Scale Cogeneration

After completing the literature review, Paper IV, it was concluded that the most suitable application for closed externally fired gas turbines, from a Swedish perspective, would be for small-scale, decentralized cogeneration of power and heat from a biomass fuel. It is not considered feasible to include a topping or bottoming power cycle to increase the electric efficiency in this case. The high fuel utilization resulting from cogeneration will compensate for the relatively low electric efficiency imposed by the temperature limitations in the high temperature heat exchanger. The generated heat could be utilized for district heating, which is already a common practice in Sweden today. The proposed gas turbine system could also be an attractive option in certain industries that already have a tradition of cogeneration, such as the pulp and paper industry or the lumber industry. Biomass is a CO₂ neutral, domestic fuel that is presently available as a byproduct from the well-developed forest industry. A future possible change in the farming practice to production of energy crops would further increase the supply of biomass fuels. A plant size of <10 MWₑ is considered suitable for this study. In this size range, the gas turbine cycle would still be able to operate with a high electric efficiency, while the efficiency of the conventional steam Rankine cycle is low. The capital cost of the closed cycle gas turbine plant is believed to be relatively low compared to a steam turbine plant of the same size.

5.4.1 System Configuration

Figure 5.2 illustrates the layout of the different system configurations considered in this study.
A more detailed description listing the primary input parameters are found in Paper V, VI, and VII. A brief description of the combustion and gas turbine subsystems is given in the following chapters.

### 5.4.1.1 Combustion Subsystem

As shown in Figure 5.2, an atmospheric circulating fluidized bed (CFB) furnace is selected for the combustion subsystem, as CFB furnace technologies feature positive attributes such as fuel flexibility, high combustion efficiency, and inherently low NOx levels. A CFB furnace is also capable of combusting fuels with a high moisture content, up to 60% (wt). In the systems in Figure 5.2, the combustion section of the CFB furnace is refractory lined so the heat is transferred to the cycle.
via the flue gas heat exchanger (FGHX) and the external bed heat exchanger (EBHX). The CFB furnace is designed for solid biomass firing at a fuel input rate of 7.7 MW (LHV) in the form of chips or sawdust. The size of the plant corresponds to a research-scale CFB plant located at Chalmers University of Technology in Gothenburg, Sweden.

The design characteristics of the combustion subsystem are carefully chosen with respect to corrosion/erosion issues and material availability. The two-stage heating in the FGHX and EBHX minimizes corrosive effects, since the highest temperature heat exchange occurs in the EBHX using heated sand from the CFB instead of the more aggressive products of combustion. The working fluid temperature is limited to 550°C in the FGHX in order to keep tube temperatures at levels where corrosion problems connected to the melting of alkali salts from biomass are lessened. Even though the EBHX experiences the most severe conditions, high-grade steel alloys appear to be suitable because temperatures and pressures are relatively low (i.e., 850°C and 12 bar maximum). In addition, because of the high heat transfer rate in the EBHX, the unit's size and cost can be reduced.

Lastly, the combustion air is preheated using heat from the flue gas. The remaining heat in the flue gas is recovered for district heating purposes in the flue gas condenser. Here both the sensible and latent heat of the flue gas is utilized as the flue gas is cooled below its dew point and a part of the water content condensed. Flue gas condensation is also used for emission control. The condenser acts as an efficient particle filter and some gaseous pollutants are also captured.

5.4.1.2 EFGT Subsystem

In keeping with future trends in gas turbine systems, various state-of-the-art components have been selected for use with the EFGT cycles, Figure 5.2. A high performance recuperator is used in combination with intercooling for enhanced heat recovery. District heat is provided from the intercooler and postcooler at the same time as the compressor inlet temperatures are lowered. The working fluid is heated to 550°C in the FGHX. The final heating of the working fluid takes place in the EBHX. The maximum temperature of the working fluid is set to 800°C. Blade cooling of the turbine should therefore not be necessary. A pressure of 2 bar(a) has been assumed for the low pressure compressor inlet, as this value balances heat transfer advantages with the need to keep stresses at a minimum.

Two different operation options have been considered. In the one-level cooling mode, the district heating network provides for all the cooling. This places a limit on the post- and intercooler working fluid outlet temperature to 65°C. Additional cooling using 15°C cooling water is considered in the two-level cooling mode in order to boost power output. The post- and intercooler working fluid outlet temperature is then reduced to 30°C.

The three working fluids chosen for the closed EFGT system shown in Figure 5.2(a) – helium (He), nitrogen (N₂), and a helium/carbon dioxide (He/CO₂) mixture – represent gases which are nontoxic, nonflammable, relatively low in cost, and compatible with a wide range of materials. These working fluids have been selected based on previous investigations on the influence of gas turbine working fluid on cycle performance, heat transfer, turbomachinery design etc. presented in
From a heat transfer point of view, He is advantageous since it has a high value of thermal conductivity, while N₂ closely resembles air as a working fluid, implying that standard turbomachinery could be more easily utilized. Even though N₂ has similar thermodynamic and fluid dynamic properties as air, N₂ provides a non-oxidative environment in the heat exchangers, which prohibits oxidative corrosion. Previous studies identified a 60% He/40% CO₂ mole fraction mixture as a working fluid which exhibits desirable characteristics related to heat transfer and turbomachinery requirements (Lee et al., 1982, Pierce 1981).

The open cycle configuration, Figure 5.2 b, allows for either series or parallel coupling with the furnace. Valve VI may be adjusted so that 100% combustion air is fed to the furnace via the gas turbine exhaust (series flow case, Air-s), while the remaining gas (about 80% of the total flow) is passed through the postcooler to produce district heat. In contrast, the parallel flow case (Air-p) allows for the gas turbine and the furnace to operate independently.

5.4.2 Thermodynamic Results

5.4.2.1 Efficiencies as a function of Pressure Ratio

The goal of the simulations was to determine the operating conditions yielding maximum power output for each cycle configuration and working fluid under the given restrictions. With the fuel input fixed, the pressure ratio \( \pi \) is thus the primary variable for analysis. Figure 5.3 illustrates three key subsystem performance efficiencies as a function of \( \pi \) for the CFB EFGT cycle system, using air and He/CO₂ as the working fluid.

In the performance analysis, electric efficiency is the key value of interest. It can be shown that the electric efficiency, \( \eta_e \), is equal to the product of the gas turbine cycle thermal efficiency, \( \eta_{th,c} \), the furnace efficiency, \( \eta_f \), and the generator efficiency, \( \eta_{gen} \). eq. 5.1:

\[
\eta_e = \eta_{th,c} \cdot \eta_f \cdot \eta_{gen}
\]

Figure 5.3 EFGT cycle system thermodynamic performance versus compressor pressure ratio, two-level cooling: closed symbols, He/CO₂; open symbols, air (parallel), Paper VI and VII.
The cycle thermal efficiency, defined as cycle power output divided by heat input to the cycle, describes the cycle power conversion efficiency. The furnace efficiency, defined as the heat transferred to the cycle (in this case through the heat exchangers EBHX and FGHX) divided by the fuel supplied to the furnace, characterizes the furnace-to-cycle heat integration while the generator efficiency specifies the generator's ability to transform mechanical power into electric power.

The cycle thermal efficiency shows a trend characteristic for recuperated cycles: after reaching a maximum, $\eta_{thc}$ continues to drop at higher pressure ratios due to decreased recuperation. Optimum conditions for the electrical efficiency do not necessarily coincide with cycle thermal efficiency because of furnace-to-cycle heat coupling. As can be seen from eq. 5.1, aside from a dependency upon cycle thermal efficiency, $\eta_e$ is also dependent upon the amount of heat supplied by the furnace, which can be quantified by the furnace efficiency. At low pressure ratios, the temperature at the recuperator cold side outlet is sufficiently high so that the amount of heat available to the cycle is limited. As the pressure ratio is raised, the cycle is able to extract increasing amounts of heat from the furnace, thus augmenting $\eta_f$ and $\eta_e$. A leveling out of these parameters occurs once the furnace air preheat temperature $T_{pa}$ falls below the design condition, as the heat input to the cycle begins to level off at this point. For the configurations shown in Figure 5.3, this point is reached at $n_c = 5$, and at higher pressure ratios $\eta_e$ is relatively constant. Hence, the design point has been selected to correspond with this location.

Another key figure that describes the performance of the system is the total efficiency. It is defined as the total usable energy leaving the system, i.e. in this case the electric power plus the heat transferred to the district heating network, divided by the fuel heat input. The simulations show that the total efficiency decreases with increasing pressure ratio as the temperature of the flue gas entering the flue gas condenser decreases.

### 5.4.2.2 Results at Design Point Pressure Ratio

Table 5.1 shows the resulting thermodynamic performance for the different system variations at the design point with component efficiencies according to Paper VI and VII.

Table 5.1 EFGT cycle thermodynamic performance results. Assumed component efficiencies according to Paper VI and VII.

<table>
<thead>
<tr>
<th>cooling</th>
<th>He</th>
<th>He/CO₂</th>
<th>He/N₂</th>
<th>Air-series</th>
<th>Air-parallel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_c$</td>
<td>2.8</td>
<td>2.8</td>
<td>5.2</td>
<td>5.1</td>
<td>4.8</td>
</tr>
<tr>
<td>$\dot{m}$ (MW)</td>
<td>2.36</td>
<td>2.71</td>
<td>2.49</td>
<td>2.83</td>
<td>2.50</td>
</tr>
<tr>
<td>$\dot{Q}_{in}$ (MW)</td>
<td>5.75</td>
<td>3.99</td>
<td>5.60</td>
<td>4.12</td>
<td>5.60</td>
</tr>
<tr>
<td>$\eta_e$</td>
<td>30.7</td>
<td>35.3</td>
<td>32.5</td>
<td>36.8</td>
<td>32.6</td>
</tr>
<tr>
<td>$\eta_{tot}$</td>
<td>105.5</td>
<td>87.2</td>
<td>105.4</td>
<td>90.4</td>
<td>105.5</td>
</tr>
</tbody>
</table>


The value of $\pi$ at the design point depends primarily on the specific heat ratio, $\gamma = c_p/c_v$, of the working fluid used, with a high value of $\gamma$ giving a low $\pi$. The specific heat ratio for He is 1.67 while it varies between 1.3 and 1.4 for the other working fluids.

### Influence of Working Fluid and Cooling for Closed Cycles

For the closed EFGT cycles, He shows slightly lower electric efficiency compared to the He/CO$_2$ mixture and N$_2$, which have nearly identical values. With respect to power output, the best performance is achieved with two-level post/intercooling, which results in an increase in electrical efficiency of nearly five percentage points for each of the cases considered (i.e. 35-37% (LHV) as compared to 31-33%) due to the lower compressor inlet temperatures. On the other hand, one-level post/intercooling maximizes the total efficiency ($\eta_{tot}$), as additional district heat is produced in favor of electricity. The total efficiency is 106% (LHV) with one-level cooling compared to 87-90% with two-level cooling ($\eta_{tot}$ can rise above 100% since flue gas condensation is employed). With one-level cooling, all the heat supplied to the cycle is either converted to power or used for district heating. However, with two-level cooling, heat is rejected to the environment with the cooling water, thus lower total efficiencies are seen. With one-level cooling, the total efficiency is independent of the working fluid. However, with two-level cooling, a certain variation in total efficiency is observed with respect to working fluid used. This observation is explained by the different behavior of the working fluids' specific heat capacity, $c_p$, on variations in temperature. The mass flow rate of the working fluid is determined so that the working fluid temperature in the EBHX is increased from 550 to 800°C with a constant heat duty at the design point. From an energy balance for EBHX, it can be concluded that $\dot{m} \cdot c_p$ over EBHX has the same value regardless of the working fluid. At lower temperature levels, the $c_p$ for N$_2$ and CO$_2$ decreases while it remains constant for He. As a consequence, the heat loss with the cooling water when cooling from 65°C to 30°C in the inter- and postcooler is lower with N$_2$ and He/CO$_2$ as the working fluid than with He.

### Open vs. Closed Cycles

In comparing open and closed cycle configurations, it is generally found that the closed EFGT cycles have a higher total efficiency. In the closed cycles, the heat remaining in the exhaust exiting the postcooler is recycled and brought to a higher temperature level through compression, as opposed of being vented to the atmosphere as in the open cycle. On the other hand, the open EFGT cycles have a higher electric efficiency due to the lower LP compressor inlet temperature (ambient temperature). The exception to this general observation is in the series connected open EFGT cycle with two level cooling. In this case, the electrical efficiency is lowered due to the higher turbine back-pressure required to overcome the CFB furnace pressure drop, and the total efficiency is increased because turbine exhaust is used as combustion air.
5.4.2.3 Influence of Pressure Drop

As noted from Table 5.1, the electric efficiency of the EFGT cycles shows variations depending on which working fluid is chosen. These differences can be fundamentally linked to exergy destruction related to pressure drop in different cycle components. In Paper VII, it is shown that the loss of exergy due to a pressure drop ($Ex_{loss}$) can be described by eq. (5.2), assuming an ideal gas, constant specific heats, and adiabatic conditions and that the mass flow rate $\dot{m}$ may be related to a known heat input rate, $Q_h$, and temperature increase of the working fluid, $\Delta T_{in}$, via the energy equation:

$$Ex_{loss} = \frac{1}{c_p M} \frac{\dot{Q}_h T_s}{\Delta T_{in}} \ln \left( \frac{1}{1 - \Delta P/P_{in}} \right)$$

(5.2)

For the various EFGT systems presented in this study, values of $\dot{Q}_h$, $\Delta T_{in}$, and $\Delta P/P_{in}$ are equivalent in each case, so exergy losses due to heat exchanger pressure drops are proportional to the inverse of the mole-based specific heat, $c_p = c_p \cdot M$. Since $c_p$ is about 30% lower for He as compared to the other working fluids, the exergy losses should be most apparent for He. Figure 5.4 illustrates this statement by showing the electrical efficiency as a function of normalized pressure drop. With the pressure drop equal to zero, $\eta_e$ converges to a single value for the closed cycles, while the open cycles show slightly better performance due to lower compressor inlet temperatures. As the pressure losses are increased, performance drops off in a nearly linear fashion for each case. All working fluids except He have a similar slope, and open and closed cycles have a constant offset over the range studied. Helium, however, shows a more pronounced pressure loss penalty due to the reasons stated above.

![Figure 5.4 Effect of pressure drop for different EFGT working fluids, 1-level cooling.](image-url)
5.4.2.4 Influence of Component Efficiencies

The results presented in Table 5.1 are obtained while assuming rather high but still realistic component efficiencies. The influence on the electric efficiency of these component efficiencies is of interest.

The turbomachinery, i.e. compressors and turbine, efficiency has a strong influence on the electric efficiency by decreasing the cycle thermal efficiency, eq. 5.1. A difference of 6-8 percentage points in electric efficiency is found when the electric efficiencies obtained in Paper V, with assumed compressors and turbine isentropic efficiencies of 0.85, are compared with the results obtained in Paper VI and VII, with polytropic turbine and compressor efficiencies of 0.90. (A polytropic efficiency of 0.90 is at the design point in the cases studied approximately equivalent to a compressor isentropic efficiency of 89% and a turbine isentropic efficiency of 92%).

By observing Figure 5.4, it can be concluded that the electric efficiency is greatly affected by the pressure drops induced in the heat exchangers. The numerous heat exchangers make the system very sensitive to this loss. As mentioned in Chapter 5.4.2.3, using He as working fluid further increases the sensitivity to pressure drops, compared to the other working fluids studied.

The effectiveness of the recuperator affects the internal heat recovery in the cycle which in turn affects the cycle thermal efficiency and thereby the electric efficiency. The sensitivity analysis in Paper V shows that when the effectiveness is decreased from 0.95 to 0.90 the electric efficiency decreases with less than 0.5 percentage points.

The influence of the air preheating temperature has also been investigated. This parameter influences the exhaust heat recovery and thereby the furnace efficiency. Simulations have shown that the electric efficiency is lowered by approximately 2 percentage points for every 100°C decrease in air preheat temperature.

5.4.3 Size of Equipment

The size of the gas turbine cycle equipment as a function of the working fluid used is investigated in Paper VI. The size of the equipment is of interest since it has an influence on the cost of the plant.

The size of all of the heat exchangers in the cycle has been calculated, assuming equivalent relative pressure drops regardless of working fluid and configuration, Figure 5.5. In general, the largest total heat transfer areas result when two-level post/intercooling is utilized. The closed cycle configuration is especially sensitive in this circumstance, as two additional heat exchangers are required for increased cooling. Cycle configuration and working fluid have little influence on the FGHX size, since heat transfer is limited on the flue gas side rather than the tube side, as seen in Figure 5.5. For the other components, heat transfer depends more strongly on the cycle-side characteristics, as the EBHX, postcoolers, and intercoolers have large film coefficients external to the cycle. In this instance, He exhibits the smallest areas, although the He/CO₂ mixture has comparable values. Cycles featuring N₂ or air, conversely, require more substantial heat transfer areas, especially with respect to postcoolers and intercoolers. He features the smallest recuperator size, and the
differences between the working fluids roughly correspond to those shown with postcoolers and intercoolers, Paper VI.

Simplified analytical techniques derived from Cohen et al. (1986) and Hunter (1994) have been used to calculate the dimensions of the turbomachinery to form a basis for comparison of the influence of the working fluid on this component group. The number of stages required for the turbine and compressors and their approximate dimensions are shown in Paper VI. As illustrated in Figure 5.5, turbomachinery size is most closely related to the type of working fluid used. The small difference seen between the number of stages and dimensions of the closed cycle gas turbine with N₂ as the working fluid and the two open cycle gas turbines is related to the lower volumetric flow rate resulting from pressurization of the closed cycle. Helium requires about three to four times the number stages compared to the open cycles for both the turbine and the compressors, which is mainly due to its high specific heat.

The size of the heat exchangers and the turbomachinery can be further reduced for closed cycle gas turbines by increasing the absolute pressure level. In Paper VII, it was found that the heat transfer areas in some heat exchangers could be reduced by a factor of 2-3 from the baseline case when the maximum pressure was set to 30 bars. However, this does not necessarily translate into cost reductions. Operating at elevated pressures increase the requirements on the strength of the material and might decrease component efficiencies which leads to increased cost and decreased thermodynamic performance.

![Figure 5.5](image-url)

**Figure 5.5** Size of heat exchangers and number of compressor and turbine stages, two-level cooling.
Although He has been shown to have the best performance in terms of heat exchanger size, the necessity of more complex turbomachinery may negate this benefit. The system featuring a He/CO₂ mixture lies between the two extremes. It requires about half the number of compressor and turbine stages compared to the pure He case. Additionally, the heat transfer area required is less than for air and N₂ working fluid.

5.4.4 Economics

Paper VII accounts for an approximate economic analysis of the externally fired gas turbine cycle systems.

An estimate of the installed equipment cost for each EFGT system configuration was performed by collecting information from equipment manufacturers and other reliable sources. The costs presented are for the first plant built and does therefore not include any advantages of mass production.

The calculated installed equipment costs for the 8 MWₚ plant with different working fluids and configurations ranges from 7.3 to 7.9 MS, with the lowest cost for He one-level cooling and the highest cost for Air-s two-level cooling. Calculations show that specific total plant costs range from 3300-3800 $/kWₑ. The error range for these estimations is estimated to be ± 20%. Further details on these calculations, together with the individual equipment costs, may be found in a report by Anheden (1999).

The total plant costs are relatively independent of the particular EFGT system configuration. An investigation of how the total installed equipment cost is divided between the different components shows that the CFB furnace and the power generating equipment make up the major part of the installed equipment cost. The CFB furnace and the power generation equipment each contribute with about 1/3 of the total equipment cost for all of the EFGT systems studied. The cycle-side heat exchangers comprise 12-17% of the total equipment cost, depending on working fluid and cycle configuration. When exploring the influence of the working fluid, it can be seen that the closed cycle gas turbine systems with non-conventional working fluids have lower heat exchanger costs (and marginally lower total costs) due to the benefits of pressurization and higher heat transfer coefficients.

The economic viability of the EFGT systems is determined by calculating the cost of electricity, (COE), for the different plant configurations. An estimate of the COE can be obtained by assuming that this cost is made up of four terms: capital charges based on annualized total plant cost; fuel cost; operation and maintenance costs; and return on district heating. District heat credit is calculated from the avoided costs for purchasing and running a biomass fueled hot water boiler. The resulting COE as a function of operating hours is found in Figure 5.6 together with the crediting used for district heat, (COH). A 5% interest rate and 25 years economic life are used in the calculations.

As can be seen, COE is strongly dependent on the annual full load hours. This means that it is important to have high plant availability and a high demand of the products, i.e. heat and power, during a major part of the year. The average annual operating period for this kind of municipal heat and power production plant in Sweden is approximately 4000-5000 full load hr/yr.
Analysis of Gas Turbine Systems for Sustainable Energy Conversion

A higher operating time is expected if the plant is used for industrial cogeneration, with a demand for process heat throughout the year instead of just during the cold season. A possible application lies with the sawmill industry with a heat demand that would cover operating times of up to 7000-8000 hr/yr. Comparing the different plant configurations, the closed cycles with one-level post- and intercooling reveals the lowest COE, with a cost of about 75-60 $/MWh for 4000-5000 hr/yr. The calculated COE for the open cycle configurations with one level post/intercooling is somewhat higher, ranging between 81-67 $/MWh for the same operating time. Using two level cooling results in a slightly higher COE primarily due to the lower district heat generation. With 7000 hr/yr, the COE is about 49-58 $/MWh.

One major uncertainty in the analysis is the cost of the turbomachinery for the closed cycle gas turbines, especially with He and He/CO₂ working fluid. The same cost has been used for all turbomachinery in the above analysis. However, in addition to the costs associated with added stages in the case of He and He/CO₂ working fluid, the necessity of having specially designed turbomachinery will also increase the cost of this component. It is, therefore, of interest to determine the allowable turbomachinery cost increase leading to a maximum allowable penalty in COE. Results show that with 4000 full load hours per year, the additional cost of turbomachinery for He or He/CO₂ working fluid should be limited to approximately 25% of the baseline turbomachinery cost in order to keep total plant costs below a reasonable margin. For N₂ working fluid, a modest modification of existing turbomachinery is expected, since the thermophysical properties of N₂ are similar to air. The closed cycle gas turbine with N₂, however, operates at a higher pressure at the compressor inlet and turbine outlet (2 bar(a)), leading to a reduction in size via a more favorable volume-specific power output. It is estimated that this improvement, in economic terms, would translate into a slight reduction (about 5%) in total specific plant cost and COE.
One of the major discussions during the course of collecting economic data was determining the material needed for the EBHX. After consultation with equipment manufacturers, stainless steel SS2333-23 was finally selected since the sulfur content of the fuel is low and erosion was thought to be of greatest concern. However, should a more exclusive alloy be required, the cost of the EBHX is estimated to increase by up to a factor of three. A sensitivity analysis shows that increasing the EBHX cost by this factor raises the capital cost by less than 5%, which also leads to a similar increase in COE with an operating period of 4000 h/yr.

5.4.5 Comparison with Other Biomass Based Technologies

To place the thermodynamic and economic results presented for the 8 MW{sub f} EFGT systems into perspective, a comparison is made to conventional and emerging technologies for small-scale heat and power generation from biomass fuels. The selected configurations for comparison include conventional steam turbine cogeneration plants, with and without flue gas condensation. A small-scale IGCC plant and a diesel engine plant fueled with a vegetable oil have also been included in the study, as they represent emerging technologies for biomass-based cogeneration. A comparison is also made with an existing 3 MW{sub f} steam turbine plant in Mälå, Sweden, which has nearly the same size as the EFGT systems considered in this study. However, the Mälå plant does not have a flue gas condenser. The thermal and economic data for these systems are summarized in Table 5.2.

Comparing the electrical efficiency of the EFGT plants, Table 5.1, with the steam turbine plants shows that the 2.5-3 MW{sub f} EFGT cycles are capable of reaching electrical efficiencies that are on the same level as a 50 MW{sub f} steam turbine plant in cogeneration operation; moreover, high total efficiencies are retained. The electrical efficiency of the EFGT plants is, however, lower than that of the IGCC plant and the diesel engine, although total efficiencies are higher.

To be able to compare the different plant configurations' total efficiency while distinguishing between heat and power generation, a dimensionless number called cogeneration effectiveness, \( \kappa \), based on fuel consumption has been developed. It is defined as the extra fuel required for separate generation of power and heat, divided by the fuel consumption in the cogeneration plant, \( \text{eq (5.3)} \).

### Table 5.2 Thermal and economic data for small-scale biomass cogeneration plants

<table>
<thead>
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<tr>
<td>Electric power (MW)</td>
<td>25</td>
<td>50</td>
<td>10</td>
<td>30</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>District heat (MW)</td>
<td>62</td>
<td>125</td>
<td>30</td>
<td>30</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Electric Efficiency (%LHV)</td>
<td>31</td>
<td>31</td>
<td>27</td>
<td>42</td>
<td>37</td>
<td>18</td>
</tr>
<tr>
<td>Total Efficiency (%LHV)</td>
<td>110</td>
<td>110</td>
<td>108</td>
<td>85</td>
<td>80</td>
<td>85</td>
</tr>
<tr>
<td>Investment ($/kW{sub f})</td>
<td>2 200</td>
<td>2 005</td>
<td>2 329</td>
<td>3 234</td>
<td>1 100</td>
<td>3 019</td>
</tr>
</tbody>
</table>
Table 5.3 Cogeneration effectiveness. Numbers in parenthesis refer to two-level cooling. Reference values, $\eta_{bl,nu} = 42\%$ (LHV) (150 MW$_e$ condensing Bio ST cycle), $\eta_{th,nu} = 110\%$, Paper VII.

<table>
<thead>
<tr>
<th></th>
<th>EFGT</th>
<th>EFGT</th>
<th>EFGT</th>
<th>Bio ST</th>
<th>Bio ST</th>
<th>Malá</th>
<th>Bio-IGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>0.44 (0.35)</td>
<td>0.41 (0.37)</td>
<td>0.38 (0.33)</td>
<td>0.38</td>
<td>0.46</td>
<td>0.04</td>
<td>0.40</td>
</tr>
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</table>

The calculated number gives the fuel saved through cogeneration as opposed to separate generation, per fuel input to the cogeneration plant. These fuel savings can be translated into reductions in emissions of environmentally harmful substances and conservation of fuel resources. The calculated $K$s for the solid biomass fueled plants are found in Table 5.3. The cogeneration effectiveness of the EFGT plants compares well with both the steam turbine plants and the IGCC plant. The closed EFGT cycle arrangement seems to be preferable to the open cycle arrangement, and one-level cooling better than two-level cooling, from this perspective, since these configurations give a higher value on $K$. The cogeneration effectiveness of the Malá plant appears to be low, which is mostly due to the lack of flue gas condensation.

An economic comparison between the different biomass-fired plants has also been conducted, as illustrated in Figure 5.7. The COE for the EFGT systems is about 80% higher than the 10-50 MW$_e$ conventional steam-based technology when considering an operating period of 4000-5000 hr/yr. If a comparison is made between the EFGT systems and the small scale Malá plant, the difference in COE is reduced to about 30%. It is noteworthy that both the IGCC plant and the diesel engine-based alternative have higher COE's (about 30% and 170%, respectively) than the EFGT systems. The extremely high costs associated with the diesel engine-based system are primarily due to the expense of the vegetable oil, (75 $/\text{MWh}_f$ as opposed to 13.75 $/\text{MWh}_f$ for solid biomass fuel). The IGCC plant is penalized by its high capital cost and low district heating production resulting from a low total efficiency. The high capital cost is the main reason for the high COE of the EFGT plants in comparison with steam turbine plants. The EFGT plant capital cost is, however, expected to decrease if these plants are put into mass production.

In order to compare the plants on a more equal basis, the EFGT systems are scaled to match the size of the Bio ST 3K plant and the IGCC plant in terms of district heat production (30 MW$_{th}$), keeping electrical and total efficiencies constant, Paper VII. In addition, a second resizing of the EFGT is considered whereby the fuel input is matched to that of the Malá plant. (Scaling based on district heat output is not appropriate here since the Malá plant does not utilize flue gas condensation.) The comparison shows that the COE for the EFGT systems lies in the same range as the steam turbine plant, especially for intermediate or prolonged yearly operating hours, Paper VII. The EFGT systems have a definite advantage when compared to IGCC at this size, as the COE's are only half as large. Favorable COE's are also demonstrated for the EFGT systems as compared to the Malá plant.
5.5 Discussion and Conclusions

The present investigation explores small-scale cogeneration of power and heat from a solid biomass fuel using an externally fired gas turbine cycle. Gas turbine cycles with either an open working fluid circuit using air as working fluid or a closed working circuit using He, He/CO₂ or N₂ as working fluid are analyzed.

The results from the thermodynamic study indicate that the electric and total efficiencies for the EFGT plants are comparable or even better than conventional Rankine steam turbine plants of comparable size in cogeneration operation. An electric efficiency in the range of 32-38% (LHV) can be reached while maintaining a high total efficiency.

The electric efficiency is sensitive to the compressor and turbine efficiencies. If a high electric efficiency is desirable, an efficient and well-designed turbomachinery is necessary. Intercooling of the compressor provides a good way of decreasing the power demand for compression and increases the possibilities of internal heat recovery in a recuperator. The electric efficiency is also sensitive to induced pressure drops. It can therefore be concluded that it is important to minimize pressure drops within the system, especially when using He as the working fluid since He is more sensitive to this loss than the other suggested working fluids.

A high total efficiency is reached by minimizing cooling of the gas turbine system by rejecting heat directly to the environment. However, minimizing cooling has a negative effect on the electric efficiency since it gives a higher compressor inlet temperature resulting in a higher power demand for compression. Using flue gas condensation to recover the latent heat in the flue gas is another way of improving the total efficiency, especially with a high-moisture-content fuel like wet biomass.

Using an open cycle gas turbine as opposed to a closed cycle gas turbine eliminates the need of a cooler before the low-pressure compressor inlet and decreases the cooling demand, since fresh air enters the compressor at environmental temperature and pressure. A higher electric efficiency is reached in the open cycle.
system when the environmental temperature is lower than the compressor inlet temperature of the closed cycle system, assuming all the other parameters are the same. However, the total efficiency of the open cycle system is lower since sensible heat leaves the open system with the exhaust.

Using a closed gas turbine cycle system allows for pressurization of the low-pressure side of the gas turbine and thereby more compact and possibly less expensive equipment. The closed cycle arrangement improves the part load performance of the system, which is of importance if the system is expected to operate at part load for extended periods of time.

Using a CFB furnace to supply the heat to the EFGT system seems to be a technically reliable solution. CFB combustion gives low emissions and is suitable for solid, high moisture content fuels like biomass, peat or solid waste products. Letting the final heating of the working fluid take place in an external fluidized bed heat exchanger where the heating is provided by the sand from the CFB-furnace prevents direct contact between the corrosive flue gases and the high temperature heat exchanger material. Corrosive and fouling effects should therefore be decreased compared to gas- to flue gas heat exchangers. The high heat transfer rate in the external fluidized bed also decreases the heat transfer area requirements and the cost of this piece of equipment compared to a gas-gas heat exchanger.

It has been shown that of the working fluids studied, He requires less cycle side heat transfer area relative to the other suggested working fluids. However, the number of stages on the turbine and compressor is increased. The He/CO₂ mixture offers a good combination of small heat transfer area and reasonable number of compressor and turbine stages. Using N₂ as the working fluid, on the other hand, makes it easier to use standard turbomachinery designed for air as the working fluid while the risk of oxidative corrosion is decreased.

The economic analysis shows the major part of the equipment cost is made up of the CFB furnace and the power generating equipment. The total plant cost is estimated to 3.3-3.8 k$/kWₑ for a first commercial plant. It is not likely that the decrease in heat exchanger cost, in the case of using He or He/CO₂ mixture as the working fluids, outweighs the cost of redesigning the turbomachinery for a small-scale plant. Therefore, a closed cycle system using N₂ or air as the working fluid or an open cycle system seems to be the most preferable options.

The cost of electricity is estimated to 73-84 S/MWhₑ for 4000 hr/yr of full load operation for the 8 MWₑ cogeneration plant. EFGT plants offer the advantage of a higher electric efficiency at a comparable or possibly lower COE when compared to conventional steam turbine plants in a small scale (<10 MWₑ). A lower COE is shown in comparison with a small-scale IGCC plant or a vegetable oil fueled diesel engine. The COE of the 8 MWₑ plant seems high when compared to the estimated COE of 30-40 S/MWhₑ of new fossil fuel based power plants or the 1998 average price of electricity of about 15 S/MWhₑ on the spot market at the Nordic Power Exchange, Nordpool, (Swedish National Energy Administration, 1999). A subsidy or higher costs of fossil fuels, for instance through an increased CO₂ tax, is needed to make power generation with biomass fuels in this scale profitable. Another case that would make the small scale EFGT cycle economically competitive is if the fuel could be obtained practically free of charge as a waste product from an industrial operation.
It is also important to remember that the economical evaluation of the EFGT plant has been made for a single-unit plant. Mass production of the plant is likely to further reduce the capital cost and thereby make it more cost competitive.

5.5.1 Suggestions for Future Work and Identification of Critical Issues

The development of high temperature material and the design and construction of high temperature heat exchangers are believed to be the main areas of future research and development of externally fired gas turbine systems. Construction of a combustion system that minimizes the risks of fouling and corrosion of the heat exchanger is desirable. The integration between the high temperature heat exchanger and the combustion device is another important area to be investigated.

Different schemes for integration of a heat recovery system with the gas turbine cycle system and the combustion system should be further examined. A study on evaporative heat recovery through humidification of the gas turbine working fluid has been performed (Ahlroth et al., 2000). The study shows that a slight increase in electric efficiency can be expected.

It might turn out to be more appropriate to optimize the gas turbine system with respect to low equipment cost rather than electric efficiency. The use of inexpensive but less efficient equipment such as a low-cost turbine and compressor system based on turbo charger technology could prove to be economically viable. Intercooling of the compressor through injection of water that evaporates rather than using an intercooler heat exchanger is another idea that has been suggested but not yet examined from an economic point of view, (Bardi, 1999).

Regarding the closed cycle gas turbines, the turbomachinery needs to be modified to allow for efficient operation with a positive pressure at the compressor inlet and turbine outlet. If a working fluid with fluid properties other than air is used, the compressor and turbine require redesigning.

It is necessary to develop a dynamic model of the EFGT plant. This would allow studies of operational transients. A control system needs to be specially designed for EFGT plant. A procedure for start-up, shut-down and load changes have to be identified. If a CFB furnace like the one proposed in this thesis is to be employed, development of an advanced control system is necessary so that the temperature fluctuations in the CFB can be controlled.

The most critical issue for a commercial breakthrough for externally fired gas turbines today is the successful operation of a demonstration plant. Proven high availability and reliability of the combustion system and the high temperature heat exchanger are of vital importance, since these are critical issues that affecting the willingness to invest in this technology.
6 Concluding Remarks

It is notoriously difficult to predict the future, but that should not stop us from making our plans on the basis of where present trends are leading us and considering what actions or events could alter these trends. Reductions in the use of fossil fuel resources and other measures to prevent rapid changes in the climate due to greenhouse gas emissions are today thought to be necessary to provide for a sustainable development. Although the effects of increased CO₂ levels on global climate are uncertain, there is scientific consensus that a significant increase of atmospheric CO₂ concentrations could have a variety of serious environmental consequences. We, therefore, need to continue to develop efficient energy conversion processes and utilize renewable energy sources so that we can save fuel resources and reduce environmentally harmful emissions related to human activities.

Using Chemical Looping Combustion to provide for energy efficient separation of CO₂ from power plants using fossil fuels is one of many promising technologies in the transition to a energy system built on renewable, CO₂ neutral energy sources. Developing technologies like externally fired gas turbine power plants for efficient cogeneration of power and heat from a renewable and CO₂ neutral solid biomass fuel with high overall fuel utilization even in a small-scale conserves natural resources. The predicted technical difficulties for the implementation of these technologies should not prevent us from investigating them but rather drive us to find the solutions to the problems.
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9 Nomenclature

\begin{itemize}
\item \(c_p\): specific heat, constant pressure (J/kg·K)
\item \(\tilde{c}_p\): specific heat, constant pressure (J/mole·K)
\item \(c_v\): specific heat, constant volume (J/kg·K)
\item \(\dot{E}_x\): exergy flow rate (J/s), (W)
\item \(\Delta H\): heat of reaction (J/kg)
\item \(M\): molecular weight (kg/kmole)
\item \(m\): mass flow rate (kg/s)
\item \(p\): pressure (N/m²)
\item \(\Delta p\): pressure drop (N/m²)
\item \(\Delta p/p_{in}\): component pressure drop relative to inlet pressure (-)
\item \(\dot{Q}\): heat transfer rate (J/s)
\item \(\dot{Q}_{in,e}\): cycle heat transfer rate, \(\dot{Q}_{in,ex} + \dot{Q}_{in,ex}\) (J/s)
\item \(\overline{R}\): universal gas constant, mole based (J/mole·K)
\item \(T\): temperature (K)
\item \(\dot{W}\): power (J/s), (W)
\item \(\gamma\): specific heat ratio, \(c_p/c_v\) (-)
\item \(\eta_e\): electric efficiency, \(\dot{W}_e/\dot{Q}_f\) (- LHV)
\item \(\eta_f\): furnace efficiency, \(\dot{Q}_{in}/\dot{Q}_f\) (- LHV)
\item \(\eta_{gen}\): generator efficiency, \(\dot{W}_r/\dot{W}_{in}\) (-)
\item \(\eta_{th,e}\): cycle thermal efficiency, \(\dot{W}_s/\dot{Q}_{in,e}\) (-)
\item \(\eta_{tot}\): total efficiency, \(\dot{W}_e + \dot{Q}_{in}/\dot{Q}_f\) (- LHV)
\item \(\pi\): total pressure ratio, \(p_{out}/p_{in}\) (-)
\item \(\kappa\): cogeneration effectiveness (-)
\end{itemize}

**Suffix**

- \(l\): one-level cooling
- \(2\): two-level cooling
- \(p\): parallel
- \(s\): series

---

Nomenclature

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### Subscript
- $0$: environmental condition
- $ap$: air preheater
- $ax$: axis
- $C$: combustion
- $ci$: LP compressor inlet
- $co$: HP compressor outlet
- $cogen$: cogeneration plant
- $dh$: district heat, district heat plant
- $e$: electricity, electric
- $el$: electric power plant
- $f$: fuel
- $GT$: gas turbine
- $in$: in (through EBHX)
- $loss$: loss
- $Ox$: oxidation
- $Red$: reduction
- $ref$: reference
- $Tot$: total

### Acronyms
- **ASU**: Air Separation Unit
- **CC**: Combined Cycle
- **CCGT**: Closed Cycle Gas Turbine
- **CFB**: Circulating Fluidized Bed
- **CFC**: chlorofluorocarbons
- **CHP**: Combined Heat and Power
- **CLC**: Chemical Looping Combustion
- **COE**: Cost of Electricity
- **COH**: Cost of Heat
- **ch**: chemical
- **DOE**: (US) Department of Energy
- **EBHX**: External Bed Heat Exchanger
- **EFCC**:Externally Fired Gas Turbine Combined Cycle
- **EFGT**:Externally Fired Gas Turbine
- **EU**: European Union
- **ex**: exergy
- **FGHX**: Flue Gas Heat Exchanger
- **GT**: Gas Turbine
- **HAT**: Humid Air Turbine
- **HP**: High-pressure
- **HRSG**: Heat Recovery Steam Generator
- **HThx**: High Temperature Heat Exchanger
- **HWC**: Hot Water Central
- **Hx**: Heat exchanger
- **IC**: Intercooler
### Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IGCC</td>
<td>Integrated Gasification Combined Cycle</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>LHV</td>
<td>Lower Heating Value</td>
</tr>
<tr>
<td>LP</td>
<td>Low-pressure</td>
</tr>
<tr>
<td>LWR</td>
<td>Light-Water Reactor</td>
</tr>
<tr>
<td>Me</td>
<td>metal (or metal oxide with low oxidation number)</td>
</tr>
<tr>
<td>MeO</td>
<td>metal oxide</td>
</tr>
<tr>
<td>NGCC</td>
<td>Natural Gas Combined Cycle</td>
</tr>
<tr>
<td>ODS</td>
<td>Oxide-dispersion Strengthened</td>
</tr>
<tr>
<td>OECD</td>
<td>the Organization for Economic Cooperation and Development</td>
</tr>
<tr>
<td>Ox</td>
<td>Oxidation reactor</td>
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<tr>
<td>PC</td>
<td>Postcooler</td>
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<tr>
<td>PFBC</td>
<td>Pressurized Fluidized Bed Combustion</td>
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<tr>
<td>Red</td>
<td>Reduction Reactor</td>
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<tr>
<td>SETS</td>
<td>Sorbent Energy Transfer System</td>
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<tr>
<td>ST</td>
<td>Steam Turbine</td>
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<tr>
<td>STIG</td>
<td>Steam Injected Gas Turbine</td>
</tr>
<tr>
<td>V</td>
<td>Valve</td>
</tr>
<tr>
<td>YSZ</td>
<td>Yttria Stabilized Zirconia</td>
</tr>
</tbody>
</table>