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FUEL EFFICIENCY

Jason K. Bernard
Editor

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PREFACE

Fuel efficiency is a form of thermal efficiency, meaning the efficiency of a process that converts chemical potential energy contained in a carrier fuel into kinetic energy or work. Overall fuel efficiency may vary per device, which in turn may vary per application, and this spectrum of variance is often illustrated as a continuous energy profile. This book presents current research data from across the globe in the study of fuel efficiency, including the study of a new CO2 capturing PGS that has a high-efficient NPGE by utilizing waste heat from factories; government intervention to promote the development of increasingly resource productive and efficient systems of energy production and consumption in Japan; as well as improving fuel efficiency of compression ignition engines fueled with vegetable oil. Chapter 1- It is becoming more important to realize CO_2-capturing power generation systems (PGSs) for drastically decreasing an amount of CO_2 emissions into the atmosphere. However, net power generation efficiency (NPGE) of a CO_2-capturing system has been considered to be significantly decreased, since capturing CO_2 requires a considerable additional amount of energy. This paper proposes a new CO_2-capturing PGS that has a high-efficient NPGE by utilizing waste heat from factories. As an example of a waste heat, exhaust gas with temperature 200 °C from ironworks is adopted. In the proposed system, the temperature of saturated steam produced by utilizing the waste heat is raised by combusting fuel in a combustor using pure oxygen instead of air. The resulting high temperature gas, composed mainly of H_2O and CO_2 gas, is used as the main working fluid of a gas turbine PGS. It is estimated that the proposed system has a fuel-to-electricity NPGE (fuel efficiency) of 60.8%, when turbine inlet temperature (TIT) is assumed to be 1000 °C. The economics of the proposed system is also evaluated and the CO_2 reduction cost is estimated to be small; 0.06 US $/(t-$CO_2$) compared to that (8.15 US $/(t-$CO_2$)) of a conventional steam turbine PGS using the same waste heat. It is shown that the proposed system is estimated to become economically feasible if a CO_2 emission credit higher than 5 $/(t-$CO_2$) can be applied to. It is also shown that CO_2-capturing is not cost-consuming but becomes to be profitable owing to improved power generation characteristics, when the TIT is increased from 1000 °C to 1200 °C.

Chapter 2- For much of the last century Japan experienced one of the fastest rates of economic growth in the world. In this paper they argue that one of the main drivers of this growth was the successful introduction of new technologies that have significantly improved the efficiency with which primary energy (exergy) is converted into useful 'energy services' delivered to the economy. They construct an economy wide fuel exergy database that illustrates the transition in the structure of Japan's energy supply, dominant energy conversion technologies and principal end-uses over the past century. They present a theory of growth that complements the descriptive Rostow model of 'staged development' but extends it quantitatively. This enables us to reproduce historical economic growth trends based on the consumption and usage of energy (exergy) by society. From this perspective they consider the role of resource scarcity as a major driver of technological progress in energy conversion technologies. They highlight the importance of dynamic and co-evolving government intervention to promote the development of increasingly resource productive and efficient systems of production and consumption.

Chapter 3- It is now a well established fact that vegetable oils can be directly used as fuels in diesel engines after suitable fuel modification. They are renewable, biodegradable, non-toxic and contain no sulphur and aromatics. However, their reduced thermal efficiency with increased hydrocarbon, carbon monoxide and smoke emissions is mainly due to their complex chemical structure with high viscosity and poor volatility. In the present research work different methods to improve the fuel efficiency of raw Honge oil operated compression ignition engine is reported and compared with a standard diesel fuelled engine. A single cylinder water cooled, direct injection diesel engine variable compression ratio developing a power output of 3.7 kW at 1500 rpm was used. The various parameters considered for the engine study include injection timing, injection pressure, injection rate, injector hole geometry and compression ratio, All these parameters were optimized to improve the engine efficiency suitably.

Initially base line data was generated with diesel and raw Honge oil. Subsequently Honge oil was converted into its methyl ester to obtain its biodiesel called Honge oil Methyl Ester [HOME]. As a part of improving fuel efficiency of HOME, it was blended with diesel in different proportions to obtain B20, B40, B60 and B80 blends [B100 refers to pure Honge biodiesel or HOME]. Further studies include focus on blending of HOME with ethanol in proportion of 5, 10, 15, and 20%. Use of biodiesel-ethanol fuel blends in diesel engines still has problems and needs to be properly addressed. It is learnt from the literature that blending biodiesel with more than 20% ethanol leads to various problems of fuel separation and corrosive effects of fuel pipelines. The amount of ethanol added was optimized based on improved brake thermal efficiency. In the last phase of the work, the HOME was blended with oxygenates like Diethyl Ether [DEE]. Results were obtained by adding small quantities of oxygenates of DEE namely 5, 10, 15 and 20% by volume to HOME. The amount of oxygenates added was optimized based on the better engine performance.

On the whole it is concluded that HOME leads to good performance at all outputs compared to raw Honge oil. The blends of HOME with diesel in general, and B20 in particular results in the improved engine performance. Blending small quantity of ethanol and DEE with HOME will enhance the engine performance.

Chapter 4- Industrial combustors such as furnaces, heaters, kilns, ovens, and dryers are among the largest energy consumers in industry. Many of them were built years ago and often are not well sealed which leads to excessive air leakage into the combustors. This air infiltration, sometimes called inleakage or *tramp air*, can significantly reduce fuel efficiency. Excessive air leakage into a combustion process reduces the fuel efficiency, primarily because of the added heat load from the tramp air which absorbs energy that is carried out the exhaust stack. Air leaks may be caused by cracks in the wall, sight ports improperly sealed or left open, failure to close air registers for burners that are out of service, improper sealing of penetrations through the combustor walls, and improper control of the pressure in the combustor when the pressure is too negative. In some cases, another important detrimental effect of excessive air infiltration is to increase pollution emissions such as carbon monoxide (CO) and nitrogen oxides (NOx), depending on the amount of tramp air and where it enters the combustor. Tramp air can also indirectly adversely affect the combustion process, which can further reduce fuel efficiency due to incomplete combustion. This chapter analyzes how excess air infiltration reduces fuel efficiency and can adversely affect other performance parameters such as NOx, common sources and causes for leaks, and how the size and location of the leak and the combustor draft level affect the amount of air infiltration and possibly burner performance. Techniques are recommended for detecting air leaks, how to correct them, and how to operate combustors to minimize leak effects.

Chapter 5- Biodiesel derived from oil crops is a potential renewable and carbon neutral alternative to petroleum fuels. The viability of these first generation biofuels production is however questionable because of the conflict with food supply. Unfortunately, biodiesel from oil crops, waste cooking oil and animal fat cannot realistically satisfy even a small fraction of the existing demand for transport fuels. The share of biofuels in overall fuel consumption was still marginal in 2008 (less than 1%). However, at the time of writing in mid-2009, rising food prices and reportedly poor energy balances, particularly from first generation biofuel crops have led to their use being questioned widely at both global and local levels. Microalgal biofuels are a viable alternative. Like plants, microalgae use sunlight to produce oils but they do so more efficiently than crop plants. Oil productivity of many microalgae greatly exceeds the oil productivity of the best producing oil crops. In this paper, review of the Microalgae as a source of fuel has been presented and an attempt has been made to propose a methodology for biodiesel production from microalgae along with environmental and economic consideration of microalgal biodiesel.

Chapter 6- Improved Energy-Efficiency helps not only in enhancing competitiveness through cost reduction but also in minimising environmental degradation. This chapter attempts to determine these factors in the German and Colombian manufacturing industries. Based on the primary data from both countries, the factors that could influence energy efficiency performance are studied. These factors are classified a priori under three categories: Economical Factors, Production Factors, and Political Instruments. The results in both countries should indicate that energy management for the manufacturing industries is important within the business strategy and that the quantification and assessment of energy consumption and energy efficiency are input indicators to improve and optimise processes within a business strategy. Moreover, the results show that in German manufacturing industry, an adequate combination of economical, production and political strategies is the key to achieve better energy efficiency performance, whereas in the Colombian case, improvements in energy efficiency are closely related with economical and production factors. The results suggest that energy policy should include legal and fiscal instruments to generate conditions to improve energy efficiency in the manufacturing industries.

CONTENTS

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Chapter 1

EVALUATION OF A CO_2-CAPTURING HIGH-EFFICIENCY POWER GENERATION SYSTEM FOR UTILIZING EXHAUST GAS FROM IRONWORKS

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ABSTRACT

It is becoming more important to realize CO_2-capturing power generation systems (PGSs) for drastically decreasing an amount of CO_2 emissions into the atmosphere. However, net power generation efficiency (NPGE) of a CO_2-capturing system has been considered to be significantly decreased, since capturing CO_2 requires a considerable additional amount of energy. This paper proposes a new CO_2-capturing PGS that has a high-efficient NPGE by utilizing waste heat from factories. As an example of a waste heat, exhaust gas with temperature 200 °C from ironworks is adopted. In the proposed system, the temperature of saturated steam produced by utilizing the waste heat is raised by combusting fuel in a combustor using pure oxygen instead of air. The resulting high temperature gas, composed mainly of H_2O and CO_2 gas, is used as the main working fluid of a gas turbine PGS. It is estimated that the proposed system has a fuel-to-electricity NPGE (fuel

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efficiency) of 60.8%, when turbine inlet temperature (TIT) is assumed to be 1000 °C. The economics of the proposed system is also evaluated and the CO_2 reduction cost is estimated to be small; 0.06 US \$/(t-CO_2) compared to that (8.15 US \$/(t-CO_2)) of a conventional steam turbine PGS using the same waste heat. It is shown that the proposed system is estimated to become economically feasible if a CO_2 emission credit higher than 5 \$/(t-CO_2) can be applied to. It is also shown that CO_2-capturing is not cost-consuming but becomes to be profitable owing to improved power generation characteristics, when the TIT is increased from 1000 °C to 1200 °C.

***Keywords*:** Carbon capture and storage, oxy-combustion, fuel efficiency, exhaust gas, economic evaluation, high efficiency, simulation

1. INTRODUCTION

The importance of reducing carbon dioxide (CO_2) emissions into the atmosphere for mitigating global warming is increasingly being recognized. Improving net power generation efficiency (NPGE) is a fundamental way to reduce CO_2 emissions from power plants for power industries. Utilization of waste heat or energy included in waste material such as municipal refuse is one of fundamental ways to achieve energy saving [1-3]. However, it is not enough to reduce CO_2 emissions by way of energy saving.

Notably, capturing CO_2 from exhaust gas at thermal power generation systems (PGSs) is considered to be an effective means of drastically reducing CO_2 emissions into the atmosphere. CO_2 capturing technologies include pre-combustion, post-combustion, and oxy-combustion methods [4-6]. Among them, the oxy-combustion method has the novel feature of being a semi-closed system and hence, in principle, can capture nearly 100% of produced CO_2 [7,8]. Furthermore, it generates no thermal nitrogen [9-11]. To produce oxygen (O_2), however, equipment for O_2 production and considerable additional energy are required. This adversely affects both the efficiency and economics of the CO_2-capturing PGS.

However, if a CO_2-capturing PGS with significantly high fuel-to-electricity efficiency (denoted by η_f) compared with a conventional PGS with an ordinary NPGE, can be realized, it will be possible to reduce necessary fuel consumption, the required quantity of O_2 for combusting fuel, and the power required for liquefying the captured CO_2 in generating the same amount of electric power energy. Here, η_f is defined as the ratio of the net generated electric power energy to the fuel energy consumed in the PGS. The η_f is also referred to as *fuel efficiency* in the following.

Based on this concept, the present author has proposed oxy-combustion PGSs, where solar thermal energy [12-14] or relatively high-quality waste heat [HQWH] from factories [15-17] is used to increase the value of η_f by producing relatively high-quality steam [RHQS]. Here, the HQWH and RHQS refer to waste heat and steam having a temperature higher than 200 °C, respectively. Hence, these systems suffer the drawback that system location is limited to sites where a large quantity of solar thermal energy or HQWH is available.

The objective of the present paper is to propose a CO_2-capturing PGS that can utilize relatively low-quality waste heat (LQWH) from factories. Here, LQWH refers to waste heat, the temperature of which is lower than 200 °C and cannot produce an RHQS. The LQWH is considered to be easily obtained compared to the HQWH.

As an example of an LQWH, an exhaust gas from ironworks with temperature 200 °C is adopted. First, a conventional steam turbine power generation system (STPS) is evaluated, and the STPS is shown to be economically infeasible. Second, a CO_2-caputuring PGS based on gas turbine (GT) technologies and on the oxy-combustion method [10-17], is proposed to utilize the exhaust gas. The thermodynamic characteristics of the proposed system are evaluated, by setting its turbine inlet temperature (TIT), for example, at 1000 °C. Third, it is shown that the proposed system achieves an economic feasibility when a CO_2 emission credit higher than 5 US \$ per 1 ton of captured CO_2 is applied to the captured CO_2.

The proposed system is based on GT technologies, so that it is not difficult to increase the TIT. It is finally evaluated how much the thermodynamic characteristics and economics can be improved when the TIT of the proposed system is increased to 1200 °C.

2. Outline of the Systems

2.1. Outline of an Exhaust Gas from Ironworks

Table 1 shows the assumed major characteristics of an exhaust gas from ironworks, adopted as an example of a waste heat from factories [18]. As can be seen from Table 1, the flow rate of the exhaust gas is 175 kNm^3/h (228 t/h), and the exhaust gas temperature is relatively low, namely 200 °C. We can see therefore that it is impossible to produce an RHQS by using this waste heat.

Table 1. Assumed major characteristics of the exhaust gas from ironworks.

Item	Assumed value
Temperature of exhaust gas	200 °C
Flow rate of exhaust gas	175 kNm^3/h (228 t/h)
Volume compositions of exhaust gas (%)	CO: 0.3, CO_2: 23.5, O_2: 2.3, N_2: 68.1, H_2O: 5.8

It should be noted that no characteristics of the ironworks are changed by utilizing the exhaust gas, except the temperature of the exhaust gas exhausted to the atmosphere after utilization.

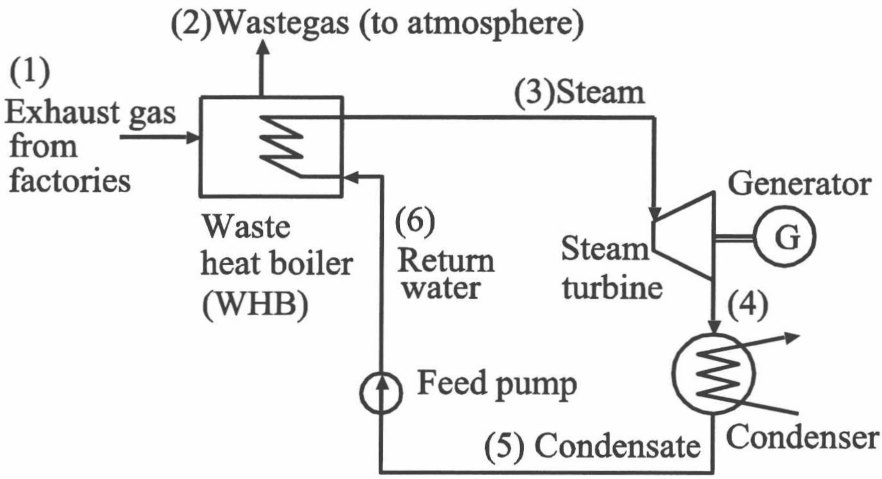

Figure 1. Schematic of a conventional steam turbine power generation system for utilizing waste heat from factories.

2.2. Outline of a Conventional Steam Turbine System

Figure 1 shows the schematic of a conventional STPS for utilizing waste heat from factories. As shown in Fig. 1, steam produced at a waste heat boiler

(WHB) by using heat energy included in the exhaust gas from factories is used to generate power by driving a steam turbine (ST) generator.

2.3. Outline of the Proposed System

Figure 2 shows the schematic of the proposed CO_2-capturing power generation system. The proposed system generates power by driving a kind of GT. The GT in the proposed system is referred to as an H_2O turbine to distinguish it from a conventional GT in which air is used as the working fluid. The proposed system is also referred to as the proposed CO_2-capturing power generation system (PCPS) hereafter.

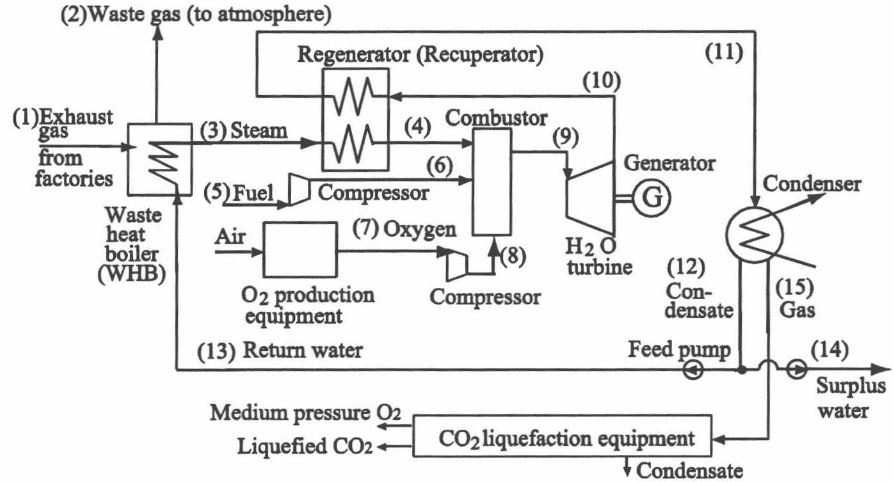

Figure 2. Schematic of the proposed CO2-capturing power generation system forutilizing waste heat from factories.

In the proposed system, as shown in Fig. 2, low-temperature steam produced at the WHB by using the LQWH from factories is utilized as the main working fluid of the H_2O turbine (HT), and its temperature, after being raised by a recuperator (regenerator), is increased to a high temperature, for example 1000 °C, by combusting fuel in a combustor by using pure oxygen instead of air. The obtained high temperature gas, composed mainly of H_2O and CO_2 gas, is used for driving a generator connected to the HT. The energy included in the HT outlet gas is used to raise the temperature of the low-temperature steam by making use of the regenerator, and is then cooled in a condenser. Most of the steam included in the regenerator outlet gas is condensed at the condenser outlet. The condensate is compressed by a feed pump and returned to the WHB to produce the steam; the excess water, not required to return, is compressed to the atmospheric pressure (1 atm was assumed to be 101 kPa) to discharge it from the system. The condenser outlet gas includes CO_2 gas, which is produced as a result of a combustion reaction of the fuel, surplus O_2 gas, which is injected into the combustor to secure complete combustion of the fuel, and H_2O gas, which is not condensed and remains as the state of saturated steam. Thus, the separation of CO_2 *gas*, produced as a result of a combustion reaction of the fuel, from H_2O *liquid* (condensate), can be physically and automatically performed at the outlet of the condenser in the proposed system [10-17].

The separated gas from the liquid at the condenser outlet is first cooled, for example to 7 °C, with the use of refrigerating machine (chiller) to remove the saturated steam included in the gas so as to reduce compression power, and is then compressed to high pressure, for example, to 140 ata (kg/cm^2) (13.7 MPa), by using a multi-stage compressor. The compressed gas is adiabatically expanded at the compressor outlet to obtain liquefied CO_2. A small amount of O_2 gas, which remains in the combustor outlet gas to secure complete combustion of the fuel, can also be obtained at the compressor outlet.

The liquefied CO_2 can be used for oil recovery enhancement or reused as carbon resource for synthesizing chemicals such as methanol from hydrogen if it can be inexpensively obtained by using a renewable energy source, such as solar energy, in the future [19,20], or will be sequestrated under the ground or at a deep sea bottom [21].

In the proposed system, H_2O gas, having considerably increased temperature and gaseous thermodynamic characteristics, is used as the main working fluid of the H_2O turbine. The pressure of the H_2O gas is increased when it is in a *liquid* state (water) with the use of a feed pump, and thus no compressing work of H_2O *gas* by an H_2O turbine is required. This feature is different from a conventional GT PGS, in which a large amount of air is compressed with an air compressor; that is, approximately two thirds of turbine axial power output is consumed in this air compression process from the intrinsic property of the Brayton cycle [22,23]. Both characteristics - absence of energy-consuming air compression process and use of steam having a larger heat energy compared with air as the main working fluid - make the efficiency of fuel use significantly high. Moreover, the H_2O turbine working fluid can be expanded down to a vacuum (for example, 29.4 kPa), producing a larger turbine axial power output. Hence, the value of η_f can be increased beyond 60%, as outlined in the following section (it should be noted that input steam energy is excluded in calculating the fuel efficiency from its definition). Therefore, the quantity of required O_2 for fuel combustion becomes small, and thus both the power required for producing O_2 and for liquefying captured CO_2 become small to generate the same electric power energy.

In the proposed system, the temperature of the steam is raised by combusting fuel, and thus the generated power output becomes much greater compared with the power output obtained by using conventional STPSs. That is, obtaining much greater power is possible in the proposed system and the proposed system belongs among repowering systems [24-26]. This feature is fundamentally different from a system that captures CO_2 from flue gas by using a chemical absorbent, in which the power output inevitably decreases and its power-selling income decreases [27].

The proposed system is based on GT technologies, and as such it could be easily applied to small scale [28] and medium scale PGSs [29], as well as to large scale PGSs [30,31].

Lastly, the fuel is burned using O_2 and therefore the combustion reaction takes place in the combustor without nitrogen (N_2) gas. Hence, no thermal NO_x is produced in the proposed system when carbon hydride fuel is used [9-11].

Similar to the proposed system, clean energy systems (CES) [32-36] and a PGS using the Graz cycle [36-40] have been proposed, in which H_2O (water or steam) is used as the main working fluid of turbines. It is an intrinsic property of water, however, that a large amount of heat energy is required to evaporate water [12-14], so that the energy efficiency of the CES degrades during which evaporation heat of water is supplied inside the system [36]. In a PGS using the Graz cycle, a sophisticated process is adopted to decrease fuel consumption by incorporating heat recovery processes of turbine and compressor exhaust energies and by using them for pre-heating water. Hence, the problem of needing a large heat requirement for water evaporation is alleviated for the PGS using the Graz cycle, and its efficiency can be improved over that of the CES [36]. However, this problem is not solved in the PGS using the Graz cycle as it is in the CES, whereas the proposed system can avoid this problem by utilizing a heat resource outside the system.