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# Exergy analysis and efficiency evaluation for an aluminium melting furnace in a die casting plant

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EXERGY ANALYSIS AND EFFICIENCY  
EVALUATION FOR AN ALUMINIUM MELTING  
FURNACE IN A DIE CASTING PLANT

by

Dennis Lee

A project report

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Engineering

in Program of

Mechanical Engineering

Toronto, Ontario, Canada, 2003

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## ABSTRACT

An aluminium melting furnace efficiency in a die casting plant was investigated using energy and exergy methods. Energy efficiency and exergy efficiency values were evaluated for the natural gas-fired furnace, and the efficiency improvement was analyzed before and after two new regenerative burners were installed on the furnace.

The research analyzed and compared the environmental impacts attributable to the melting furnace before and after the burner upgrading project, and also provided a financial analysis of the capital investment of the upgrading project.

The study shows that the exergy method can be used beneficially to analyze the furnace efficiency and that exergy efficiency is a more practical measure in reality. Thus, it is believed that further applications of exergy methods are desirable to a wider range of industrial and engineering applications.

From the results of comparisons, the study shows that the regenerative burner technology and staged-combustion technique can improve combustion performance, reduce fuel (natural gas) consumption and lower NO<sub>x</sub> and CO<sub>2</sub> emissions. Adopting the regenerative burner and staged-combustion technique will be beneficent to the die casting plant on energy saving and cost reduction.

Recommendations are also made for further efficiency improvements.

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## LIST OF SYMBOLS

$\bar{a}$	molar specific exergy, kJ/kmol
$A$	total exergy (availability), TJ
$\Delta A$	change of total exergy, TJ
$A/F$	air fuel ratio
$A/F_{\text{theo}}$	theoretical air fuel ratio
$c$	specific heat of incompressible substance on basis of unit mass, kJ/kg.K
$\bar{c}_f$	molar specific heat of fusion, kJ/kmol.K
$E$	total energy, TJ
$\Delta E$	change of total energy, TJ
$\bar{g}_f^0$	specific molar Gibbs function of formation at reference environment, kJ/kmol
$\bar{h}_0$	specific molar enthalpy at reference environment, kJ/kmol
$\bar{h}$	specific molar enthalpy, kJ/kmol
$\bar{h}_{RP}$	enthalpy of combustion on basis of per kmol fuel, kJ/kmol fuel
$\bar{h}_{RP}^0$	lower heating value (LHV) of fuel, kJ/kmol fuel
$\bar{h}_f^0$	enthalpy of formation per kmole at standard state, kJ/kmol
$i$	component of a mixture
$I_{CV}$	exergy destruction of control volume or a closed system, TJ
$n$	number of moles
$n_i$	coefficient of chemical reaction equation giving moles of reactant or products per mole of fuel
$p_0$	reference environment pressure, Pa or kPa
$Q$	total heat transfer, TJ
$Q_{CV}$	total heat transfer of control volume accompanying combustion, TJ
$\bar{s}_0$	specific molar entropy at reference environment, kJ/kmol.K
$\bar{s}$	specific molar entropy, kJ/kmol.K
$T_0$	reference environment temperature, K
$T_f$	final temperature in heat transfer, K

$T_i$	initial temperature in heat transfer, K
$T_{\text{comb air}}$	temperature of combustion air, K
$y_i$	molar fraction of component i of a mixture
$y_i^e$	molar fraction of component i in reference environment
$W_{\text{cv}}$	work output from control volume

### Greek Letters

$\eta$	Energy efficiency, %
$\varepsilon$	Exergy efficiency, %

### Subscripts

comb air	combustion air
comb gas	combustion gas
cg	combustion gas
fg	flue gas
preh air	preheated combustion air
m	melting process
regen	regenerator
e	component exiting system
i	component incoming system
P	product of combustion
R	reactant of combustion

### Superscripts

tm	thermomechanical exergy
ch	chemical exergy

## CHAPTER 1

### INTRODUCTION

This chapter will explore the rationale and need for the project, present a conceptual introduction to exergy, and conclude with an overview of the report.

#### 1.1 Rationale and Need for the Project

In 1992, the United Nations Conference on Environment and Development was held in Brazil. At this conference, the Rio Declaration on Environment and Development was adopted. The action plan was put into place to ensure the implementation of the Declaration against Global Warming. These agreements and subsequent new environmental regulations have resulted in requirements for reducing environmental impact from energy use.

Fossil fuels are the main form of energy sources used today. In order to control energy use, fossil fuel consumption and its emission must be controlled as well.

Natural gas, a type of fossil fuel used widely in industrial, commercial and domestic applications, provides heat after combustion and emits pollutants to the environment. Natural gas is mainly combusted in industry, for example, for heating purposes in power generation plants and melting purposes in metallurgical plants. In the industry sector, natural gas is a main fuel source that requires regulated control because of the great amount of emission accompanying combustion, even though the emissions per unit fuel energy for natural gas are lower than those for oil and coal.

In addition to environmental concerns, changes in the electricity market have caused fuel prices (including natural gas prices) to rise. The historical records show natural gas prices have increased 3.5 times in Ontario, Canada from 1997 to 2001 (Direct Energy, 2003). The unit price of natural gas has risen from 27¢/m<sup>3</sup> to 30¢/m<sup>3</sup> in December 2003, which is almost twice as much as in December 2002 (Energyshop, 2003). Direct Energy, an independent, deregulated natural gas

company, predicts that natural gas prices will continuously increase in the future. Escalating fuel expense has created a steady increase in the cost of producing natural gas.

Furthermore, when the automotive vehicle industry increases production, die casting goods are also increasing in demand, especially die casting material that has shifted from iron/steel to aluminium. The recent production of aluminium casting has increased with the demand for aluminium casting goods.

As natural gas consumption increases, rising costs and market competition often force manufacturers to enhance natural gas efficiency and reduce fuel expenses. Natural gas manufacturers are constantly seeking solutions and applying new technologies for reducing fuel consumption.

For most gas-fired furnaces and boilers, one possible answer to environmental and economic concerns is the use of regenerative burner technology. The regenerative theory is not at all new to combustion systems, but after some new techniques are applied on conventional regenerators and burners, the performance of devices need to be examined. It needs to be investigated whether or not a regenerative burner system is more efficient to combustion performance, and whether or not it is more beneficial to energy efficiency improvement on natural gas-fired furnaces, such as melting furnaces, heating furnaces and other furnaces.

The Dym Eto Casting (DEC) plant is selected here as a representative plant in which a regenerative burner system has been newly installed on an aging melting furnace. This project evaluates furnace efficiency improvement and provides comments on how to further improve furnace efficiency.

## **1.2 Exergy Method and Efficiency Evaluation**

Using energy methods to evaluate efficiency has been recognized for years, but the exergy method examines efficiency change in a more practical way. Exergy is defined as maximum theoretical work possibly obtained in a process or a system referring to environment. For example, if a flue gas exergy value is small, it shows that even if some energy is associated with flue gas, this part of energy becomes less available in reality. Exergy efficiency is a measure of how near a process

approaches ideality and a measure of how near energy transfer approaches ideal transfer. Section 2.4 shows further exergy theory review.

### **1.3 Motivation and Objective of the Study**

The motivation of this study is to identify and discuss the efficiency improvement after the implementation of a new burner system on a melting furnace. The prime objective of the study is to apply exergy analysis to a specific industrial application.

This project studied a melting and holding furnace in the DEC die casting plant after a set of regenerative burner systems had been installed on the furnace. With exergy evaluation, the efficiency improvement of the furnace is illustrated and compared to the results based on an energy evaluation.

Another objective is to examine the environmental impact caused by the furnace upgrading from the point view of exergy.

A third objective is to explore the financial benefits from the upgrading project .

Extending the influence of exergy to a wider range of industrial processes and promoting the application of the exergy theory to more users are secondary objectives.

### **1.4 Scope of the Project**

- Background introductions on the casting industry and metal die casting process.
- General introduction of exergy definitions and general principles, and comparison of exergy and energy analysis methods.
- Site visit, observation and data collection at the plant, including material logs, metering records and furnace operation monitoring on the floor.
- Thermodynamic calculations by both energy and exergy methods.

- Comparison and analysis of the calculation results.
- Discussion of the importance of exergy methodology on energy efficiency analysis and improvement.

### **1.5 Overview of the Project Report**

The main topics covered in this report are as follows:

- Background outlines of the die casting industry, typical casting processes and the importance of studying melting furnace efficiency.
- Description of the technologies applied in the upgrading project, illustration of regenerative burner operation and staged-combustion design, which are two technologies providing the possibility of efficiency improvement and emission reduction.
- Introduction of exergy and the differences between energy and exergy methods.
- Thermodynamic calculations of efficiencies using energy and exergy methods.
- Analysis of the efficiency improvement after the upgrading project, based on the results of calculation.



## **CHAPTER 2**

### **INDUSTRY, PROCESS AND PROJECT BACKGROUND**

In this chapter, the overall background of the casting industry and melting process is presented. Some energy issues, recent exergy research reviews and environmental impact from industrial processes are addressed and general financial aspects are explained. Regenerative technology is also illustrated in this chapter. In the last section of the chapter, the background of the selected plant and profile of the upgrading project are introduced.

#### **2.1 Die Casting Industry Background**

##### **2.1.1 Metal Casting Process**

The metal casting industry uses molten metal to form cast metal components that are used in a wide variety of manufactured products. The largest uses of cast metal products include motor vehicles, railroad equipment and construction materials.

The basic casting process generally involves four main steps:

- 1) Pattern making: Using metal to construct a model of the designed cast part and a mold through which molten metal can be poured into a model.
- 2) Metal melting: Melting ingot and scraps in a furnace.
- 3) Die casting: Pouring the molten metal into the mold, cooling and removing mold.
- 4) Finishing: Cleaning and coating the casting, recycling scrap.

The second step, metal melting process consumes a great amount of energy. Some melting furnaces use electricity to generate heat. The furnace in this DEC plant uses natural gas as fuel. Combustion of natural gas provides heat for the melting process.

The third step, casting process also is considered as an intensive energy consumption process. Usually cooling water is used to cool down the model. Warmed cooling water can be utilized for space heating or other heating purposes. In summer, however, cooling water rejects heat to the atmosphere through a cooling tower. The first and the last steps consume less energy as compared with the melting process.

This study focuses on the melting furnace. The furnace particularly selected in this project is a furnace with combined melting and holding functions. After the melting process when the furnace operates in a holding status, combustion takes place intermittently in order to maintain the furnace temperature and contain liquid metal. The furnace holds the molten metal a few hours before the melted metal is conveyed to the casting machine.

### **2.1.2 Increasing Aluminium Casting Production**

Generally, there are two types of metal used in die casting--ferrous and nonferrous metal. High volume production in the nonferrous sector is often made using a die-casting process. Aluminium casting has experienced continuous growth (IEC, 1998). Shipments of aluminium castings have quadrupled from the 1950s to the 1990s, with an average of 1.4 million tons per year for the first seven years of the 1990s. Aluminium castings also dominate the nonferrous sector in general, comprising 78% of total nonferrous shipments. Most aluminium cast goods are used for the automobile manufacturing industry, such as engine components, wheels and body parts, etc.

Since one kilogram of cast aluminium alloy can offset the weight of 4.95 to 5.5 kilogram of cast iron in a new automobile, the 1.4 million tons of aluminium castings could translate to over 3 million tons per year in reduced demand for iron. Manufacturers generally have felt that the benefits of reduced automobile weight has been sufficient to offset the 30 to 100 percent price premium over steel. Aluminium is three to five times as expensive as steel on a per kilogram basis, but requires only one kilogram of aluminium for each 5.5 kilogram of steel replaced. The effective cost of aluminium in automotive applications is therefore roughly 133 to 200 percent the cost of steel. The growing demands for lightweight vehicles call for increased productions of aluminium die casting. Thus a greater amount of energy is consumed by a melting furnace than before. Some questions have been raised, such as how to conserve energy sources, how to reduce fuel

consumption, how to reduce flue gas emission, etc. To answer these questions, it is necessary to study the melting furnace's fuel consumption and efficiency.

### **2.1.3 Industrial Pressure on Emission Reduction**

Besides economical drivers explained in section 2.1.2, some forces from industries, particularly from the automobile manufacturing industry, push furnace researchers and users to study and attain emission reduction of flue gas.

Industries have placed an emphasis on quality management due to increased international competition and the demands of its customers. For example, the big three U.S. automobile manufacturers have required their Tier 1, 2, and 3 suppliers to become certified in quality management standards, e.g. ISO9000 and ISO14000. These quality management systems provide opportunities of environmental performance improvement. Environmental regulation becomes another driver to study environmental protection and reduce air emission.

## **2.2 Environmental Policy Issues**

The first international official meeting to declare the need for action in terms of global warming issues was held by the Canadian government in Toronto, Canada in June 1988. The World Environmental Technology Development Congress adopted the United Nations Framework Convention on Climate Change in 1992. In addition, the Kyoto Protocol adopted the United Nations Framework Convention on Climate Change in 1997 to determine the detailed targets associated with the reduction of CO<sub>2</sub> emissions for individual developed countries by 2010. These were determined on the basis of 1990 levels and have been adopted by most of the developed countries (except United States) by 2002, including Canada.

In casting industries, by-products of high temperature combustion are essential elements to be controlled for air pollution. The two oxides of nitrogen related to combustion are nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>). NO<sub>x</sub> refers to either one of these gases, which are considered toxic and play a major role in the formation of acid rain, smog and ozone.

### **2.2.1 Pollutant Emission from the Die Casting Process**

Aluminium melting and casting industries use large quantities of energy and emit hazardous air pollutants. The industry remains one of the main sources of emissions with higher emission density than the average emission density of other manufacturing sectors (IEC, 1998). These industries strive to recover waste heat and reduce pollution.

Common sources of air emissions from die casting include the following:

- 1) Flue Gas: Consists of NO<sub>x</sub>, CO<sub>2</sub>, N<sub>2</sub> and CO, etc. High temperature combustion generates NO<sub>x</sub>. Through combustion, hydrocarbon fuel transforms to CO<sub>2</sub>, and sometimes it also transforms to CO due to uncompleted combustion. Metal oxide fumes are released while some of the metal vaporizes and condenses.
- 2) Furnaces: Fume emission and waste gas emission occur during metal injection; in fluxing and dross removal, process can give off hydrochloric acid and oxide fumes.
- 3) Mold: Gaseous emissions can originate from the molten metal itself; such as the evolution of chemicals from the lubricant as it is sprayed onto the hot metal die; and as the molten metal contacts the lubricant.

As mentioned at the beginning of Section 2.2, regulatory drivers will continue to be the main factor in industry efforts to improve their environmental performance.

### **2.2.2 Nitrogen Oxides Generation**

In high temperature combustion, the amount of NO<sub>x</sub> generation is related to flame ambient temperature and oxygen concentration of combustion air. It means that the higher flame ambient temperature, the more NO<sub>x</sub> generated; the higher oxygen concentration, the more NO<sub>x</sub> generated. In a melting furnace, combustion temperature is directly related to the flame temperature.

In normal furnace operations, when waste heat is partially recovered from flue gas and used to pre-heat intake air supplied to the furnace, the problem is that if the temperature of pre-heated air is too high, exceeding 1200 K (1700°F), the concentration of NO<sub>x</sub> in flue gases increases rapidly. As a

result, operating normal furnaces at a high temperature of preheated air and high temperature of combustion is not practical in terms of emission regulation.

Regenerative burner technology has been introduced to reduce the emerging influence of global warming and acid rain by reducing CO<sub>2</sub> emission and NO<sub>x</sub> emission. This study aims in part to examine the flue gas emission improvement that the regenerative burners can make on a melting furnace.

### **2.3 Regenerative Technology Background**

Thermal energy savings can be made in many ways. For example, unit fuel consumption could be decreased through operational improvements, such as optimizing furnace pressure controls and air-to-fuel ratios which will prevent overheating. These energy saving techniques improve combustion performance and melting efficiency thereby increasing energy savings.

Besides operational improvements, hardware improvements such as strengthening furnace insulation and furnace seals, and utilizing ceramic fibers in furnace walls, will also reduce waste heat transferred through furnace enclosure which will, in turn, save on fuel consumption.

#### **2.3.1 Waste Heat Recovery**

It is just as important to recover waste heat as it is to reduce waste heat. This is another solution to saving thermal energy. Waste heat in industries has a wide range of temperatures and exists in different forms, such as exhaust gas, exhaust steam, exhaust water, hot waste solids, hot waste liquid, heat convection, radiation from hot surfaces, and heat leaks.

The waste heat in the aluminium die casting industry is mainly generated from the melting furnace. Normal melting furnaces operate at high temperatures (often over 1000°C). If the high temperature flue gases are exhausted without heat recovery, a great deal of heat would be wasted when flue gases are emitted to the atmosphere. A regenerative burner system is often used to recover heat from the flue gases and to utilize the recovered heat.

### **2.3.2 Regenerator**

A regenerative burner system is designed for recovering heat from the flue gas, preheating air for combustion, mixing air and fuel and igniting combustion. The system consists of burner monitoring and control instruments which are also essential to the system. The regenerator is one part of a regenerative burner system.

The regenerator is a heat exchanger that is usually used for recovering waste heat in flue gases from equipment, such as the boiler or furnace. When combustion takes place in a furnace, fossil fuel (for example, coal, natural gas) and air forms high temperature products of combustion (POC) and exhausts high temperature flue gas. Before the flue gas exits to the atmosphere, making flue gas flow through a regenerator can reduce flue gas temperature and reclaim heat. The reclaimed heat is often recycled for heating purposes, for example, to heat up water before it is supplied to the boiler, to warm up the air before proceeding with combustion, or for domestic heating of the water supply.

There are various types of regenerators, such as ball regenerators, tube regenerators and honeycomb regenerators, which are defined by various media material and different forms of heat transfer. In the ball regenerator, the ceramic ball media has strong endurance for high temperatures and brings the temperature of preheated air to a level close to the temperature of flue gas, thus the ball generator offers an efficient heat recovery when compared to using conventional methods such as a tube heat exchanger.

### **2.3.3 Regenerative Burner**

The regenerative burner is usually equipped on a natural gas-fired furnace or oil fuel furnace. The burner is designed for reduction of NO<sub>x</sub> emissions generated by oxidation of nitrogen in the air. As explained in Section 2.2.2, during high temperature combustion, the concentration of NO<sub>x</sub> increases when the flame temperature is rising.

The regenerative burner ignites fuel at a lower temperature so as to reduce the flame temperature and to lower NO<sub>x</sub> concentration. The flame's chemical environment, primarily the oxygen concentration within the flame, is another important variable.

For achieving low NO<sub>x</sub> generation, combustion should be controlled to take place at the suppression of maximum flame temperature, and at the prevention of excess amounts of oxygen. At the approximate temperature of 800°C and above, the regenerative burner operates in the so-called “flameless oxidation”, a mode with an invisible flame (Flamme, 2002). Temperature distribution in the flame is very homogeneous with the advantage of low NO<sub>x</sub> concentration.

Not only the NO<sub>x</sub>, but also the CO emission level is lower than the level of the conventional counterpart because better control of the air-fuel ratio makes completed combustion. Reduced CO<sub>2</sub> emission is also achieved because less fuel is required to be consumed in the process.

A design, called adjustable directivity, optimizes the flame for various furnace types by adjusting and directing the flame toward the metal being melted, without the problem of excessive burner velocity, which could lead to excessive dross formation by constantly exposing fresh metal. This function offers the possibility to reduce solid waste generated from combustion (Schalles, 2002).

#### **2.3.4 Regenerative Burner System Operation**

The common design of the regenerative system is to flow exhaust air through a loosely packed casing of media so as to allow the flue gas to flow through but with low restrictions. This pack of media is capable of storing heat at very high temperatures (up to 1150°C, 2100°F).

There are two cycles in a typical operation of a regenerative burner system. Figure 2.1 illustrates how the system operates.

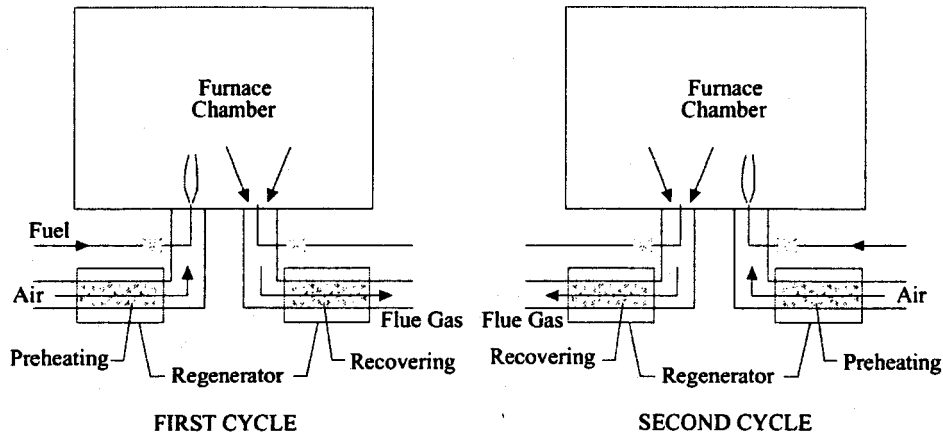


Figure 2.1 Illustration of operation for regenerative burner.

The first cycle, illustrated on the left of Figure 2.1, exhausts the flue gas to the right duct when flowing through the casing and heats up the right side media. Simultaneously, fresh air supplied to the combustion flows through the left duct while the left burner is firing. After the right side media is heated up to the desired temperature, the system will start the second cycle.

The second cycle, illustrated on the right in Figure 2.1, turns off the left burner flame, exhausts the flue gas to the left duct, heats up the left side media and switches the fresh air intake to flow through the right duct so it preheats the right side media so that the right burner starts firing. After the left side media is heated up to the desired temperature, the reverse cycle starts again. Usually one cycle takes a minimum of 40 seconds and a maximum of 90 seconds.

Regenerative burner systems sometimes are integrated as several pairs of burners to the furnace. They are alternatively operating as exhaust air ducts or inlet air ducts. Media cases must be emptied every 3~6 months and cleaned out of contaminates that accumulate and restrict the flow of exhaust gas and intake air.

The regenerator in a regenerative burner system can preheat combustion air but does not directly change the emission to enhance combustion performance and control the emission. At this point, staged-combustion is introduced.



### 2.3.5 Staged-Combustion Design Illustration

The fuel port is the major part in a regenerative burner. A technique called "staged combustion" is used to solve the NO<sub>x</sub> emission problem. Staged air and staged fuel are included in the concept of "staged combustion". This process is different from the conventional combustion principal, as combustion air and fuel are mixed twice and combustion take place in two regions, as illustrated in Figure 2.2.

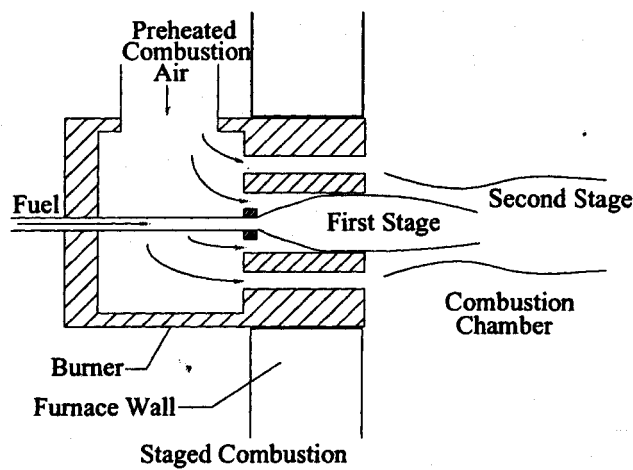


Figure 2.2 Illustration of staged combustion

The "first stage" air port is used to provide a stable operation at furnace temperatures below 1253K (980°C). Air is fed to this port to provide a cold start and low temperature combustion. The "cooler" combustion reduces nitrogen oxides generation.

At the second stage, the air is directly injected into the furnace chamber and mixed with the first stage flame to form the second stage combustion.

### 2.3.6 Example Applications

The regenerative burner technology has been adopted recently. Many users have implemented the system and succeeded in starting its practical operation. In Canada, this technology and equipment has already been applied to at least eleven furnaces in past years. The burner was made and constructed by the manufacturer, Bloom Engineering (Schalles, 2002).

Another successful example in a die casting plant, Visteon Automotive Rawsonville plant, Ypsilanti, MI, USA, which is similar to the DEC plant in this study, shows that the old 5,000 kg melting furnace had a measured energy consumption rate of approximate 5,300 kJ/kg, compared to a new rate of 2,300 kJ/kg after upgrading the burner system (Guthrie, 1999).

A new die casting line of Toyota Auto Manufacturing Inc. was established at Kamigo, Japan, in June 1999, in which the products are mainly aluminium engine blocks. A furnace with a regenerative burner was installed and achieved 21% reduction in energy usage compared to earlier lines (Shiramizu, 2001).

The regenerative burner technology allows the aluminium die casting plant to improve the melting performance and reduce flue gas emission levels. Besides economic and environmental demands, regulatory efforts seemingly will be another driver to promote regenerative technology. For instance, in Los Angeles, CA, USA, if a natural gas-fired burner is operating without implementation of the regenerative technology, it would be required to reduce operation hours in order to meet NO<sub>x</sub> emissions regulatory limits (Guthrie, 1999).

Certainly, a regenerative burner is not a solution to zero-emission problems because the furnace releases CO<sub>2</sub>. Total CO<sub>2</sub> emission elimination is possible when the natural gas is replaced by clean energy carriers such as hydrogen (Winter and Nitsch, 1990). Some researchers (Verkhivkera and Yantovskib, 2001) suggest that liquidation of CO<sub>2</sub> in flue gas gives zero emission to the environment. In that studied case, a gas-fired power plant does not need any stack or chimney and might be located in a densely populated urban area, giving all kinds of clean energy to consumers.

## 2.4 Exergy Methodology Review

The increasing awareness that the world's energy resources are limited has caused some governments to re-examine their energy policies and take measures to reduce emissions of waste. It sparks interest in the scientific community to take a closer look at energy conversion devices and to develop new techniques to better utilize the existing limited resources.

### **2.4.1 Definition of Exergy**

Exergy is defined as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to equilibrium with a reference environment. Exergy is a measure of the potential of a stream to cause change, as a consequence of not being a completely stable equilibrium relative to the reference environment (Rosen and Dincer, 1997).

Due to the irreversibility of real processes, the amount of exergy output from a process is always less than the maximum amount of exergy output possible. Hence, by analyzing the exergy loss within a process, imperfections can be evaluated and recommendations can be pinpointed. An exergy flow chart can be used to illustrate exergy flows across a system or process.

### **2.4.2 Differences between Exergy and Energy**

Generally, energy efficiency is based on the first law of thermodynamics and exergy is based on combination of first law and second law of thermodynamics. Unlike energy, exergy is not conserved and the initial exergy is destroyed at least in part by the irreversibility in any process.

The first law of thermodynamics deals with the quantity of energy and asserts that energy cannot be destroyed or created. The second law of thermodynamics deals with the quality of energy and asserts that the destruction of exergy occurs during a irreversible process (Cengel and Boles, 1998).

For example, the energy associated with 11 litres of water at 80°C is approximately 1 kJ, at room temperature, 25°C. Compared to 1 kJ of electricity, electricity is more useful than the 11 litres of water since electricity can be used for a wider range of services, e.g. heating at low or high temperatures, or providing shaft work, etc. The differences of usefulness can be evaluated by exergy value. The exergy value of 11 litres of water at 80°C in an environment of 25°C is approximately 0.16 kJ, less than the 1 kJ of electricity.

The exergy of a system or a flow is the sum of two contributions: the thermomechanical exergy and the chemical exergy, when other forms of contributions, such as kinetic exergy or potential exergy, etc., are neglected.

#### **1) Thermomechanical exergy and chemical exergy**

From the point of view of exergy, when one analyzes a system or a process with defined incoming flows to the system and outgoing flows from the system, the exergy flows balance can be expressed as:  $A_{\text{input}} = A_{\text{output}} + I_{\text{CV}}$ , i.e.,  $A_{\text{input}} \neq A_{\text{output}}$ . It shows exergy is not conserved in a real system.

When evaluating exergy, firstly, it is hypothesized that the system is brought about without a change in composition from a specified state to the state where it is in a thermal and mechanical equilibrium with the environment. Secondly, it is hypothesized that components of the system are allowed to react with environmental components to produce other environmental components beginning and ending at the environment state. The components exergy can be expressed as:  $A = A^{\text{ch}} + A^{\text{tm}}$ . The components exergy changes after chemical reaction or certain process, particularly such as combustion of hydrocarbon fuel, the change of exergy can be expressed as:  $\Delta A = \Delta A^{\text{ch}} + \Delta A^{\text{tm}}$ .

If heat transfer between two states does not involve chemical reaction, then no change of chemical exergy, i.e.,  $\Delta A^{\text{ch}} = 0$ . For the melting process, not involving chemical reaction, metal chemical exergy is cancelled between two states of the same composition. Only the thermomechanical exergy changes in melting. For the heat transfer between gas and solid, it is considered that only the thermomechanical exergy changes in the process as well. This is the exergy theory and calculation that this study is based on.

## 2) Energy efficiency and exergy efficiency

There are many types of efficiencies, the following energy and exergy efficiencies are used in this study. Energy efficiency is expressed as the ratio of product energy output to total energy input in a system or process. Exergy efficiency takes into account the losses caused by irreversibility which destroys exergy in the process. These expressions both gauge how effectively the energy/exergy input is converted to the product.

$$\text{Energy efficiency } \eta = E_{\text{product}} / E_{\text{input}} = 1 - E_{\text{loss}} / E_{\text{input}} \quad (2.1)$$

On another hand, exergy efficiency

$$\varepsilon = A_{\text{product}} / A_{\text{input}} = 1 - (A_{\text{loss}} + I_{\text{CV}}) / A_{\text{input}} \quad (2.2)$$

Contrary to energy efficiency, exergy efficiency relates to the maximum amount of work (or work equivalent; exergy efficiency also applies for non-work situations). Although this maximum can never be reached, exergy efficiencies provide an indicator to identify those areas with large improvement potentials.

Being more specific, in the melting process,  $E_{\text{product}}$  is the heat transferred to melted metal.  $E_{\text{input}}$  is the energy generated from fuel combustion.  $E_{\text{loss}}$  includes all energy lost in the system.  $A_{\text{product}}$  is the exergy transferred to melted metal.  $A_{\text{input}}$  is the exergy generated from fuel combustion.  $A_{\text{loss}}$  is the exergy associated with all energy loss in the system.

Exergy efficiency has been defined in other ways (Bejan, 1988 and Ionita, 2002). However, this study will only use the above equation 2.2 for analysis.

### 2.4.3 Exergy Research Review

The exergy method is a tool for measuring the efficiency of processes or systems, especially energy intensive systems. Some researchers have used exergy methods in many science studies and engineering applications, for example, thermodynamics (Etele and Rosen, 2001) and thermal engineering (Camdali and Tunc, 2001; Verkhivkera and Yantovskib, 2001; Struchtrup, 2002). Some discussions specifically focus on topics in air-conditioning systems such as refrigerating compressor cycling (Sagian, 2003 and Ratts, 2000), dehumidification (Ghaddar 2003), absorption (Zheng, 2001) and other psychrometric processes (Bilal, 2003). Many exergy researches are also conducted in fields of thermal storage (Dincer and Rosen, 1999), building energy management (Virtanen, 2002; Rosen, 2001), fuel cell (Cownden, 2000), thermo-economics (Dincer, 2001; Rosen, 2001). Some applications using exergy method have been studied and successfully practiced in industries like combined heat and power (CHP or cogen), building design in heat pump system and refrigeration system (Aprea, 2003), food process and sugar production (Bayrak, 2003), etc.

Meanwhile the exergy theory is used to study topics of environment impact. Any technologies that increase efficiency will use lesser resources (or exergy) to drive the processes for the same products

or services. This leads to less extraction from the environment of energy resources. When a more efficient process uses lesser resources, a direct result is normally to emit lesser wastes to the environment. Due to the character of irreversibility, exergy destruction often disorders the whole system, or destroys the order in an organized system, such as an environmental system, so irreversibility of exergy destroys or impacts on environment. (Rosen, 1986; Rosen and Dincer, 1997; Dincer and Rosen 1999). By preserving exergy through increased efficiency (i.e. degrading as little exergy as possible for a process), environmental damage is reduced. The exergy associated with processed wastes emitted to the environment can be viewed as a potential for environmental damage (Rosen and Dincer, 2001; Rosen and Dincer, 2002).

Exergy methods have been used to analyze fuel consumption and furnace efficiency improvement in the iron making industry (Petela, 2002 and Bisio 2000). Some researches (Korobitsyn, 2002) also found that the comparison of energy and exergy analysis, for a melting furnace, reveals the benefit of heat recovering in regenerator. The recovered heat can dry air which may drive air turbine to generate electricity and compressed air (by-product) for industrial production.

Besides the exergy expression shown in this study, there are other different second-law-based methods of analysis (Bejan, 1996, Sagian, 2003 and Ratts, 2000). These discrepancies of the methods are various from definitions, wordings and expressions of exergy, etc.

## **2.5 Financial Aspects**

### **2.5.1 Energy Cost in Metal Casting Industries**

Metal casting industry is an energy-intensive sector, in which fuel costs represent a large portion of total costs. Material expenditure is one of the largest proportions in overall cost structure in this industrial sector and fuel expense is an important component of material costs (NADCA, 1996).

Statistics show that energy is an important component of material cost in overall cost structure. Besides the costs of raw material and labours, the third largest cost, energy expense, is 4% of the total expenditure in nonferrous foundries (casting) sector. It is two to three times the average for manufacturing overall (IEC, 1998).

In a melting furnace system, careful evaluation of the fuel consumption, energy associated with products and wasted energy will likely reveal economic opportunities to cost savings.

### **2.5.2 Pollution Abatement Cost**

In nonferrous foundries casting industries, spending on pollution abatement and control only appears as low as 0.7% of total expenditures (Exhibit 9, IEC, 1998). Most of the spending is on operating measures rather than pollution prevention and control. This is a low capital utilization in pollution abatement cost. In the nonferrous sector, pollution abatement expenditures are more evenly distributed with the highest percentage spent on water pollution control, followed by solid waste and air pollution.

In the metal melting process, some technologies for efficiency improvement will directly or indirectly enhance the pollution prevention and will need capital investment. A regenerative burner directly reduces air pollution by reducing the NO<sub>x</sub> and CO<sub>2</sub> emissions.

As described in Section 2.1, the major competitive force in the industry is the shift from steel castings to aluminium casting. This change has led to capital replacement and the need to improve environmental controls and efficiency in the new equipment. Meanwhile, the industry faces other changes in production, such as outsourcing and import substitution. Many old and inefficient facilities are likely to become uneconomic. Upgrades or replacements could offer large reductions in fuel consumption.

Some researchers use various concepts when conducting analysis of economic on energy and exergy production processes, such as cost/quality ratio (CQR, \$/kJ) in energy method (Ionita, 2002), exergetic manufacturing cost (\$/kWh) in exergy method (Silveira, 2002), etc.

## **2.6 Background and Process of the Project**

The DEC aluminium die casting plant was established in 1965 in Toronto, Ontario, Canada. It supplied cast parts for automotive vehicles. These parts consist of engine pistons and various automobile components. The plant operates 24 hours a day, 7 days a week, about 50 weeks a year.

There are 4 melting/holding furnaces under manual operation for die casting production and 3 automatic production lines for piston casting production. Three melting furnaces were constructed when the plant was built, another one was added in the early 1990's as production was increasing. Three automotive piston lines were set up in the mid 1990's. This plant's history reflects the development of the aluminium die casting industry introduced in previous sections.

During 38 years of service, three manual operation furnaces have undergone only minor improvements but have not had any technological improvements that would have significantly changed operating efficiency. After some research, in 2002, a decision was made to replace the inefficient conventional gas burners in the melting/holding furnace operation in order to improve the melting performance, which is the first objective of the upgrading project. This is to preheat combustion air by reclaiming heat from the flue exhaust with a pair of regenerative burners to be installed on each of 3 furnaces (see Figure 2.3).

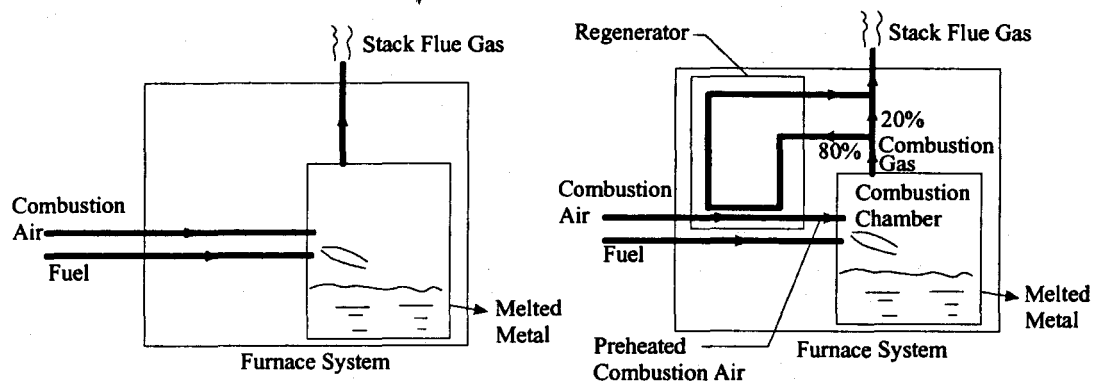


Figure 2.3 Illustration of furnace operation before and after upgrading

Figure 2.3 illustrates the change before and after upgrading. Discharge from the furnace is melted aluminium. One rectangular frame represents the combustion chamber. The largest frame represents the furnace system as a whole, which consists of the chamber, the stack and the regenerator.



To reduce natural gas consumption and fuel expense is the second objective of the project. The third objective is to reduce the NO<sub>x</sub> and CO<sub>2</sub> environmental emissions. This project will also reduce CO emission and solid waste.

This study focuses on Furnace #3, which is built with the largest capacity among four manual operating furnaces. This furnace is a direct natural gas-fired furnace. The existing condition before upgrades are explained as follows:

Ingots, scraps and hot metals are charged through a door at the side of the furnace. The melted metals are discharged at the opposite side. Two old burners were mounted at the end wall without material charge and discharge. Flue gas leaves the furnace at the opposite side to the burners.

After upgrades, two new burners are installed at the same sidewall of the two old burners. Flue gas will leave the furnace through one of the burner ducts; however, if necessary, if the regenerator is under repair, both burners will work and the flue gas will leave the furnace through the old ducts. Ceramic ball media are used in a pair of regenerators in the new system.

There are 3 types of waste exergy emissions from the melting process: the gaseous wastes exhausted through the stack, the waste heat is released to the atmosphere, and some solid wastes are discharged in the furnace. Each of these waste exergy emissions has a potential impact on the environment.

Next chapter discusses in details of energy and exergy calculations and analysis.

## CHAPTER 3

### ENERGY AND EXERGY EFFICIENCY EVALUATION AND ANALYSIS

This chapter presents data sources and information, including calculation, summary and analysis. Detailed equations and formulas are attached in Appendixes A.1.

#### 3.1 Evaluation Summary for Efficiencies

Figures and tables for material and source consumption were collected and summarized from production logs. The information of process and production was obtained from operation control system, facilities administration personnel and archived documents in the plant .

##### 3.1.1 System Schematic

The schematics in Figures 3.1 and 3.2 illustrate the process before and after upgrading project :

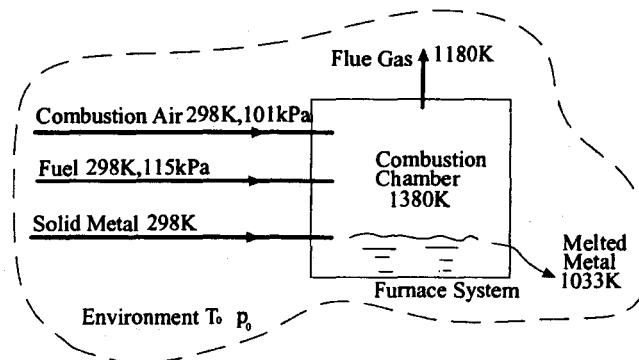


Figure 3.1 System schematic before upgrades

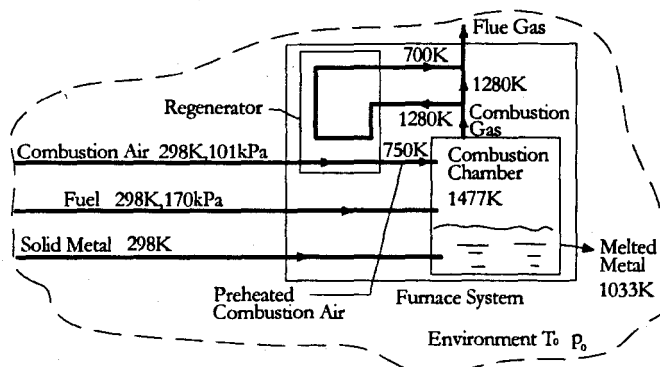


Figure 3.2 System schematic after upgrades

1) The big rectangular frame represents the furnace system, which consists of a combustion chamber, stack and regenerator (after upgrades). The small rectangular frame presents the combustion chamber where high temperature combustion takes place. The dashed rectangular frame denotes boundary of the combined system, which includes furnace system and reference environment. This study assumes a reference environment at 25°C (298K) and 1 atm ( $1.01 \times 10^5$  Pa).

2) It is worth noting that after upgrades, the regenerator is a part of furnace system but is examined as an individual device as well. One energy/exergy input to regenerator is the energy/exergy of combustion gas entering regenerator, and one energy/exergy output is the energy/exergy of flue gas exiting regenerator and exhausted through stack. Another energy/exergy input to regenerator is the combustion air, which flows through regenerator and another energy/exergy output is the preheated combustion air. These are illustrated in flow charts in section 3.2 and considered in calculations attached in Appendix A.1.

### 3.1.2 Sources and Data Tables

All data is summarized in Tables 3.1 and 3.2. Both tables list source fuel consumption, combustion air input, melted metal production and flue gas exhausted from stack. Table 3.1 presents data before upgrades and Table 3.2 shows data after upgrades.

Table 3.1 Data Source Summary Table: Before Upgrades

Item	Quantity		Temperature (K)	Pressure (10 <sup>5</sup> Pa)
Natural Gas	514,692 m <sup>3</sup>	383,198 kg	298	1.15
Combustion Air	1,837,422 m <sup>3</sup>	2,163,435 kg	298	1.01
Solid Metal	1,972,000 kg		298	1.01
Stack Flue Gas	8,809,656 m <sup>3</sup>	2,546,633 kg	1180	1.01
Melted Metal	1,972,000 kg		1033	1.01

Table 3.2 Data Source Summary: After Upgrades

Stream	Quantity		Temperature (K)	Pressure (10 <sup>5</sup> Pa)
Natural Gas	218,152 m <sup>3</sup>	240,481 kg	298	1.70
Solid Metal	1,972,000 kg		298	1.01
Combustion Air	889,710 m <sup>3</sup>	1,059,345 kg	298	1.01
Preheated Combustion Air	2,264,371 m <sup>3</sup>	1,059,345 kg	750	1.01
Combustion Gas (Enter Regenerator)	1,577,358 m <sup>3</sup>	1,039,861 kg	1280	1.01
Stack Flue Gas	8,171,142 m <sup>3</sup>	1,299,826 kg	540	1.01
Melted Metal	1,972,000 kg		1033	1.01

The following explains and justifies data collection methodology for the above tables.

#### 1. Fuel Consumption and Production Days

For reasonable comparison, this study examines the energy and exergy consumption involved in 1,972,000 kg production before and after upgrade. After upgrades, current production schedule is 3 shifts per day, 6 days per week. From December 2002 to March 2003, there are total 96 working days, but 44 working days were not operating at full production capacity due to maintenance and holiday shutdowns. Within the remaining 52 working days, total of 1,972,000 kg ingot and scraps are charged in batches. Melted metal loss occurs in melting and conveying. Since the amount of liquid aluminium loss is very small (less than 0.01 % from plant experience), it is not considered in this study. It is assumed that the same amount of melted metal is produced.

Fuel consumption data are taken from the daily log of natural gas meter readings, total 218,152 m<sup>3</sup> consumed within 53 days after upgrades. Previous material and fuel consumption is based on the latest statistics made in 1993. The assumption, that average 1 kg ingot input accompanies 0.261 m<sup>3</sup> fuel consumption, has been confirmed by product operation personnel in plant, because during past 10 years, the furnace performed consistently according to material and fuel logs. Therefore 514,692 m<sup>3</sup> gas would had been cost to produce 1,972,000 kg melted metal. Natural gas pressure was 115 kPa (2 psi) and has been increased to 170 kPa (10 psi) while new burners are installed .

Based on operation, furnace only shuts down two weeks every year for maintenance. It gives 350 working days and 24 hours per working day. This will be used for estimation in the study.

## *2. Raw Material Analysis*

For simplicity, calculations are based on a pure aluminium ingot. The actual alloy used in melting and casting production is categorized as alloy 306, whose properties are different from pure aluminium. The melting process of alloy 306 is more complicated than that of pure aluminium. But normally the specific heat value of an aluminium alloy is lower than that of pure aluminium, which means that the aluminium alloy needs less heat than the same mass of pure aluminium does if they are to reach the same temperature. From records in the plant, material alloy 306 consists of 84% aluminium, 10% Si, 3.5% Cu, 1% Fe and 1.5% other substances. Since the majority of alloy 306 is aluminium, pure aluminium is treated as material in this calculation and the properties of pure aluminium are used in the calculations. Scraps are recycled from processes in the plant and scrap quality is considered to be the same as the ingot. All terms of "material" or "ingots" in this calculation include scraps.

## *3. Combustion Air, Flue Gas and Combustion Gas*

Combustion air is supplied by a supply fan and taken directly from indoor air at the plant. To balance the plant indoor air pressure, the plant pressurization is controlled by a group of air handling units. The quantity of combustion air and the quantity of stack flue gas are computed from the quantity of fuel consumed, i.e. , based on chemical equations (A.3) and (A.4) in Appendix A.1 for before and after upgrades, respectively. In 1993, before upgrades, the plant recorded the temperature of product of combustion (POC) at 1360K (2000°F); the previous stack testing in 1993

registered the flue gas temperature at stack as 1180K (1665°F). After upgrades, the furnace monitoring system displays a mean temperature of POC 1477K (2200°F) and also records flue gas temperature at 700K (800°F) while flue gas exits regenerator. In this study, “combustion gas” is used for the gas exits furnace chamber and enters regenerator.

#### 4. Hot Charge

In order to maintain furnace temperature, after the melted metal is discharged for casting, a hot charge of melted liquid aluminium is delivered to furnace in batches at 1033K - 1088K (1400°F - 1500°F). Hot charges are held in furnace for short time (few hours) during a normal production day. After new batches of ingot enter furnace and are melted, a mixture of hot charge and newly melted metal is delivered to casting production at 1033K. Hot charge stay in the system for a short time and consumes almost no energy, therefore the hot charge is ignored in energy and exergy consumption calculation in this study.

### 3.1.3 Summary of Equations and Tables

This section explains energy and exergy balance equations and efficiency calculation for furnace system before they are tabulated in tables. The detailed balances analysis and equations for regenerator are shown individually in section 3.1.3.4 .

#### 3.1.3.1 Energy and exergy balance equations and efficiency of furnace

Refer to Figure 3.3 and 3.4, energy input and output of furnace are shown as following equations:

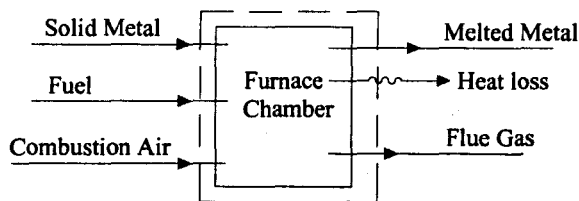


Figure 3.3 Schematic of energy balance of furnace system before upgrades

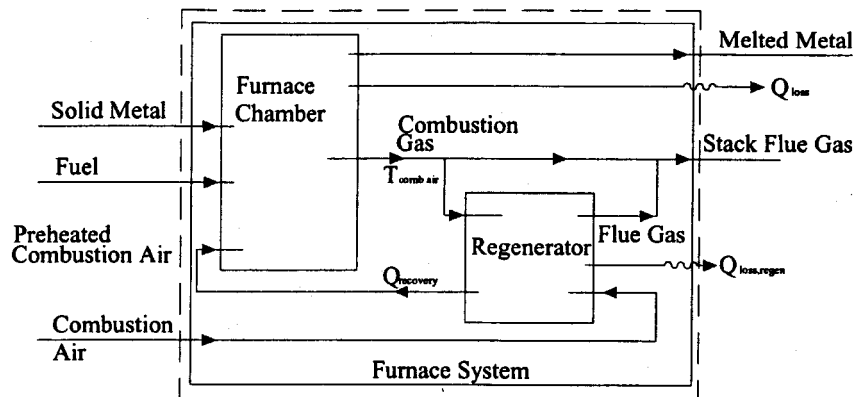


Figure 3.4 Schematic of energy balance of furnace system after upgrades

$$E_{\text{input}} = E_{\text{source}} + E_{\text{solid metal}} + E_{\text{comb air}} \quad (3.1)$$

$$E_{\text{output}} = E_{\text{melted metal}} + E_{\text{flue gas}} + Q_{\text{loss}} + Q_{\text{loss, regen}} = (E_{\text{solid metal}} + \Delta E_{\text{metal}}) + E_{\text{flue gas}} + Q_{\text{loss}} + Q_{\text{loss, regen}} \quad (3.2)$$

Energy balance equation is:

$$E_{\text{input}} = E_{\text{output}}$$

where  $E_{\text{comb air}} = 0$ ,  $E_{\text{solid metal}} = 0$ ; before upgrades  $Q_{\text{loss, regen}} = 0$ .

As referring to the following figures, exergy input and output in furnace chamber are shown as following equations:

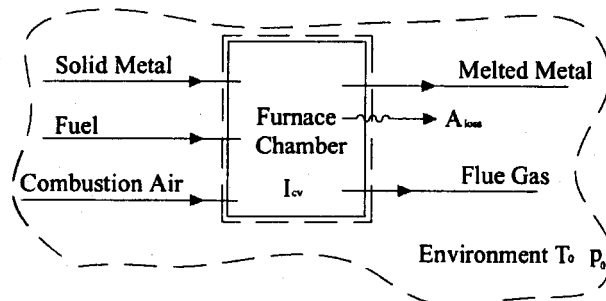


Figure 3.5 Schematic of exergy flows of furnace system before upgrades

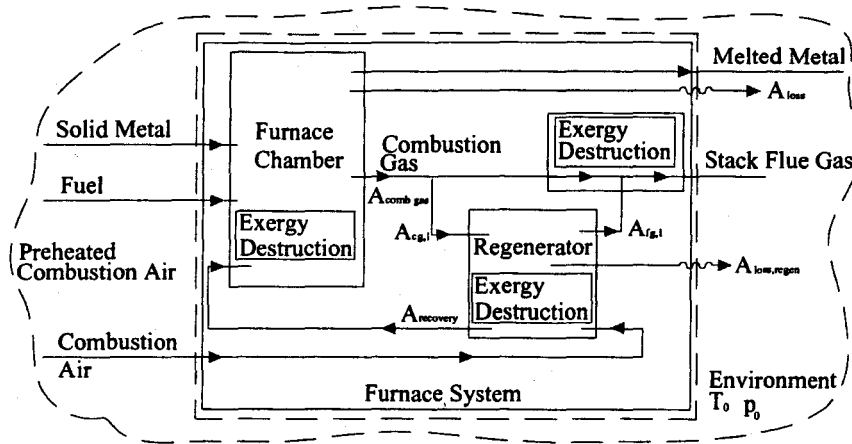


Figure 3.6 Schematic of exergy flows of furnace system after upgrades

$$A_{\text{input}} = A_{\text{fuel}} + A_{\text{solid metal}} + A_{\text{comb air}} \quad (3.3)$$

$$A_{\text{output}} = A_{\text{melted metal}} + A_{\text{flue gas}} + A_{\text{loss}} + A_{\text{loss, regen}} = (A_{\text{solid metal}} + \Delta A_{\text{metal}}) + A_{\text{flue gas}} + A_{\text{loss}} + A_{\text{loss, regen}} \quad (3.4)$$

Where  $A_{\text{comb air}} = 0$ .

Exergy balance equation is:

$$A_{\text{input}} = A_{\text{output}} + (I_{\text{CV}} + I_{\text{CV, regen}} + I_{\text{CV, mix}}) \quad (3.5)$$

Exergy is not conserved in real system:

$$A_{\text{input}} \neq A_{\text{output}}$$

The energy (exergy) loss in furnace chamber,  $Q_{\text{loss}}$  ( $A_{\text{loss}}$ ), occurs in combustion, melting and water cooling processes. The energy (exergy) loss exists in various ways, such as heat radiation and convection through structural wall, and heat leaked from furnace doors. The energy (exergy) associated with cooling water system is also part of the energy (exergy) loss. The energy (exergy) loss in furnace chamber can not be calculated directly since the lack of measuring tools, however it can be shown from energy balance equation (3.1) and (3.2) as follows,



$$Q_{\text{loss}} = E_{\text{input}} - \Delta E_{\text{metal}} - E_{\text{flue gas}} \text{ (or } E_{\text{comb gas}} \text{ for after upgrades)} \quad (3.6)$$

The exergy loss in furnace chamber is estimated as

$$A_{\text{loss}} = Q_{\text{loss}}(1 - T_0 / T_{\text{loss}}) \quad (3.7)$$

$T_{\text{loss}}$  denotes a hypothetical mean temperature of general heat loss from furnace chamber to environment. The heat loss includes all loss from furnace body, leaked through door and transferred to cooling water. The mean temperature is not a real and measured temperature, but a datum for estimating exergy loss accompanying overall heat loss.  $T_{\text{loss}} = 420\text{K}$  is taken in this study. The estimation also assumes the hypothetical temperature is not changed after upgrades (this assumption can be found in analysis A.1.3.3), the heat loss from the furnace changes very slightly from 7.97 TJ to 7.23 TJ in Table A.1.6. Therefore  $T_{\text{loss}} = 420\text{K}$  is taken for before and after upgrades.

Now from equation (3.3), (3.4) and (3.5), the exergy destruction in furnace chamber is found,

$$I_{\text{CV}} = A_{\text{input}} - A_{\text{transfer}} - A_{\text{loss}} = A_{\text{input}} - (\Delta A_{\text{metal}} + A_{\text{flue gas}}) - A_{\text{loss}} \quad (3.8)$$

The  $I_{\text{CV}}$  calculated here includes destructions of combustion, melting, water-cooling and other phenomena inside furnace chamber.

Sometimes the exergy loss and exergy destruction inside furnace chamber is taken as combination, ie.  $A_{\text{loss}} + I_{\text{CV}} = A_{\text{input}} - A_{\text{transfer}} = A_{\text{input}} - (\Delta A_{\text{metal}} + A_{\text{flue gas}})$  (equation 2 and 3, S. De, 2003). The reason why exergy loss and destruction are merged to one part is unnecessary to do so or because sometimes  $A_{\text{loss}}$  and  $I_{\text{CV}}$  are not computable due to short of monitoring data.

Energy efficiency ( $\eta$ ) of melting furnace is measured as the ratio of product energy output to source energy input. Exergy efficiency ( $\epsilon$ ) of melting furnace is measured as the ratio of product exergy output to source exergy input with consideration of exergy destructed in process. Source input energy (exergy) is associated with fuel only. Equations are:

$$\eta = \Delta E_{\text{metal}} / E_{\text{fuel}} \quad (3.9)$$

$$\epsilon = \Delta A_{\text{metal}} / A_{\text{fuel}} \quad (3.10)$$

The detailed analysis of energy and exergy balances in regenerator is shown individually in section 3.1.3.4.

### 3.1.3.2 Energy and exergy balances Tables

The following Tables 3.3 and 3.4 present energy and exergy balances of the studied furnace system for before and after upgrades. All detailed energy and exergy flows are listed in Table A.1.8 and A.1.15 in Appendix A.1.

Table 3.3 Summary of Energy Balance for Before and After Upgrades

Items	Before Upgrades		After Upgrades	
	(TJ)	%	(TJ)	%
Energy Input:				
Fuel natural gas	21.40	100	13.43	100
Combustion air	0		0	
Solid metal	0		0	
Total	21.40	100	13.43	100
Energy Output:				
Stack flue gas	11.28	53	3.25	24
Melted metal	2.15	10	2.15	16
Energy loss from furnace	7.97	37	7.23	54
Energy loss from regenerator			0.8	6
Total	21.40	100	13.43	100

Note:

- 1) 0.01 TJ or 1% tolerance of normalized value sometimes caused by round off value. This is applicable to other balance tables in this study.
- 2) Before upgrade, furnace melting efficiency  $\eta_1 = 2.15 / 21.40 = 10\%$
- 3) After upgrade, furnace melting efficiency  $\eta_2 = 2.15 / 13.43 = 16\%$

The summary of calculation results of exergy are listed below.

Table 3.4 Summary of Exergy Balance for Before and After Upgrades

Items	Before Upgrades		After Upgrades	
	(TJ)	(%)	(TJ)	(%)
<b>Exergy Input:</b>				
Fuel natural gas	21.98	100	13.95	100
Thermomechanical contribution	0.01	0.05	0.02	0.14
Chemical contribution	21.97	99.95	13.93	99.86
Combustion air	0		0	
Solid metal	0		0	
Total	21.98	100	13.95	100
<b>Exergy Output:</b>				
Stack flue gas	6.63	30	1.73	12
Melted metal	1.22	6	1.22	9
Exergy loss from furnace	2.31	11	2.10	15
Exergy loss from regenerator			0.07	0.5
Total	10.16	47	5.12	36.5
<b>Exergy destruction</b>				
in furnace	11.82	53	7.56	54
in regenerator			1.2	9
in flue gas mixing			0.07	0.5
Total	11.82	53	8.83	63.5

Notes:

- 1) Before upgrade, melting furnace exergy efficiency  $\epsilon_1 = 1.22 / 21.98 = 6\%$
- 2) After upgrade, melting furnace exergy efficiency  $\epsilon_2 = 1.22 / 13.95 = 9\%$

In this study, efficiencies of energy and exergy are summarized as follows.

Table 3.5 Furnace Energy and Exergy Efficiencies Comparison

Efficiency	Before Upgrades (%)	After Upgrades (%)	Improvement (%)
Energy	10	16	60
Exergy	6	9	50

### 3.1.3.3 Tables Analysis for Furnace

Comparing energy balance on furnace before and after upgrades, some conclusions can be found in Tables 3.3 and 3.5:

- 1) Overall system energy efficiency increases from 10% to 16% due to less source energy input ( from 21.4 TJ to 13.43 TJ) when same production is maintained, i.e. 2.15 TJ energy consumed for melting before and after upgrades. In real operation, the follows may reduce actual energy efficiency : aluminium alloy instead of pure aluminium and no electricity considered in overall energy input . After upgrades, electricity consumption could be higher than before since more motorized devices are used and more monitoring devices consume more electricity. On another hand, some other factors might increase energy efficiency, for instance, depending on production demands, less holding time and more charged ingot may operate furnace more effectively.
- 2) Energy saving 7.97 TJ ( $=21.40 - 13.43$ ) from less energy source consumption is mainly relied on better performed gas burner and regenerator. Refer to calculation Table A.1.4 in section A.1.2,  $(\bar{h}_p - \bar{h}_r)$ , the unit heat transfer from combustion based on per mole of fuel, is greatly improved, from 423,476 kJ/kmol to 625,501 kJ/kmol due to better performed gas burner which gives higher temperature of POC (1280 K vs. 1180 K) and better A/F rate (11.66 vs. 14.95), also due to regenerating system which gives higher temperature of reactant air (750 K vs. 298 K).
- 3) After upgrades, heat rejection 24% (3.25 TJ) to the environment from stack flue gas, is significantly less than before upgrades. The reduction decreases thermal impact to environment.
- 4) After upgrades, the energy loss (7.23 TJ ) to environment from furnace chamber is slightly reduced from previous loss (7.97 TJ ). It is benefited from the new monitor and control system which better operates pressure balance of combustion gas.
- 5) Before upgrades, total unused energy in system is 90% (19.25 TJ  $=11.28+7.97$ ); after upgrades, total unused energy in system reduced to is 72% (9.67 TJ  $= 4.16+7.24+1.61$ ). The overall system performance is improved.

Exergy comparison is observed from Tables 3.4 and 3.5. Some points can be found as follows:

- 1) Overall system exergy efficiency increases from 6% to 9% due to less exergy input (21.98 TJ vs. 13.95 TJ) and additional input (0.94 TJ with preheated combustion air) while same production is maintained, i.e. 1.22 TJ exergy consumed for melting.
- 2) Source exergy supplied to process after upgrades is less than before, compare to previous 21.98 TJ, a total of 8.03 TJ ( $= 21.98 - 13.95$ ) exergy saving is achieved.
- 3) As seen in Table A.1.10, molar fuel thermomechanical exergy is increased from 322 kJ/kmol to 1291 kJ/kmol. It resulted from gas pressure increased from 115 kPa to 170 kPa. However thermomechanical exergy contribution of natural gas is a small portion comparing to chemical contribution when temperature of natural gas is the same as environment, so the thermomechanical exergy contribution is sometimes ignored when calculating natural gas exergy.
- 4) Overall chemical exergy consumption reduced from 21.97 TJ to 13.93 TJ. Molar chemical exergy of fuel is improved approximate 1%, from 919,728 kJ/kmol to 928,951 kJ/kmol as shown in Table A.1.10.
- 5) Waste exergy from stack flue gas is decreased from 6.63 TJ to 1.73 TJ because of regenerating process. The reduction of waste exergy emission decreased the environmental impact. Meanwhile, 12% waste exergy of flue gas still shows the availability of the flow.
- 6) After upgrades, 9.66 TJ ( $= 2.1 + 7.56$ ) exergy loss and destruction from furnace chamber appears less than before 14.13 TJ ( $= 2.31 + 11.82$ ). It shows the furnace performance is improved. The change of exergy loss from furnace chamber, from 2.31 TJ to 2.1 TJ, is not great.
- 7) The process inside furnace chamber destroys more than 50% of exergy input before and after upgrades. The largest exergy waste in the system is the destruction in the processes of combustion, heat transfer and melting due to the nature of the furnace operation.

- 8) Exergy destruction in regenerator is 1.2 TJ (9% of total exergy input). Miscellaneous exergy loss in regenerator is only 0.07 TJ (0.5% of total exergy input).
- 9) Overall unutilized exergy reduced from 20.76 TJ (= 6.63+2.31+11.82) to 12.73 TJ (= 1.73+2.10+0.07+7.56+1.2+0.07) while retaining the same production.

For analysis and illustration, the above tables are converted to flow charts and assessed in Section 3.2.

#### 3.1.3.4 Energy and exergy balances Tables for Regenerator

Here is the calculation of the regenerator energy and exergy efficiency. The below figure is the illustration of regenerator.

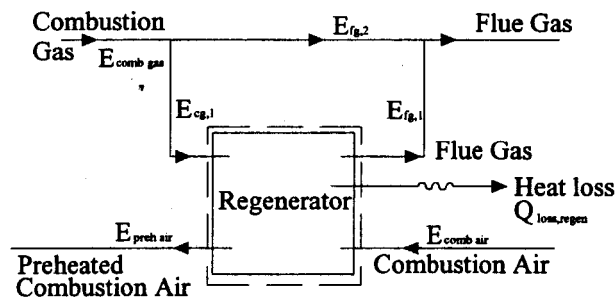


Figure 3.7 Schematic of energy flows in regenerator

In regenerator, energy balance equation is:

$$E_{\text{input}} = E_{\text{output}}$$

$$\text{Energy input to regenerator } E_{\text{input}} = E_{\text{cg},1} + E_{\text{comb air}}$$

$$\text{Energy output from regenerator } E_{\text{output}} = E_{\text{preh air}} + E_{\text{fg},1} + Q_{\text{loss, regen}}$$

$$\text{Energy loss in regenerator } Q_{\text{loss, regen}} = (E_{\text{cg},1} + E_{\text{comb air}}) - (E_{\text{preh air}} + E_{\text{fg},1})$$

$$\text{Energy (heat) recovery } E_{\text{recovery}} (Q_{\text{recovery}}) = E_{\text{preh air}} - E_{\text{comb air}}$$

$$\text{Regenerator energy efficiency } \eta_3 = E_{\text{recovery}} / E_{\text{input}}$$

In regenerator, exergy flows shown as follows:

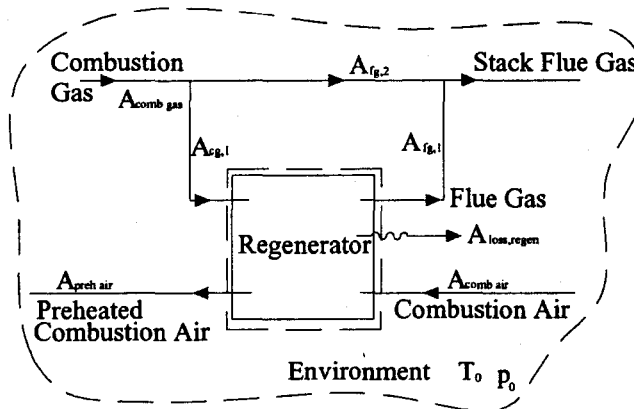


Figure 3.8 Schematic of exergy flow in regenerator

Exergy input to regenerator  $A_{\text{input}} = A_{\text{cg},1} + A_{\text{comb air}}$

Exergy output from regenerator  $A_{\text{output}} = A_{\text{preh air}} + A_{\text{fg},1} + A_{\text{loss, regen}}$

Exergy loss in regenerator  $A_{\text{loss, regen}} = Q_{\text{loss, regen}} (1 - T_0 / T_{\text{loss, regen}})$

$T_{\text{loss, regen}} = 325 \text{ K } (52 \text{ }^\circ\text{C})$  is estimated for the surface of the regenerator body because the regenerator body is warm and touchable when it operates.

$I_{\text{CV, regen}} = (A_{\text{cg},1} + A_{\text{comb air}}) - (A_{\text{preh air}} + A_{\text{fg},1}) - A_{\text{loss, regen}}$

Exergy recovery  $A_{\text{recovery}} = A_{\text{preh air}} - A_{\text{comb air}}$

Regenerator exergy efficiency  $\epsilon_3 = A_{\text{recovery}} / A_{\text{input}}$

It must be noted that the exergy destruction  $I_{\text{CV, regen}}$  exists in heat transfer processes between combustion gas and media (ceramic ball) and between media and combustion air. The following table lists energy and exergy balance for regenerator:

Table 3.6 Energy and Exergy Flows for Regenerator

Items	Energy		Exergy	
	(TJ)	%	(TJ)	%

Input:				
Combustion air	0		0	
Combustion gas (1)	5.15	100	3.21	100
Total	5.15	100	3.21	100
Output:				
Flue gas (1)	1.96	38	1.0	31
Preheated combustion air	2.38	46	0.94	29
Loss from regenerator	0.8	16	0.07	3
Total	5.15	100	2.01	63
Exergy destruction			1.2	37

Notes:

- 1) Regenerator energy efficiency  $\eta_3 = 2.38/5.15 = 46\%$
- 2) Regenerator exergy efficiency  $\epsilon_3 = 0.94/3.21 = 29\%$

For detailed calculation refer to Appendix attached.

#### 3.1.3.5 Analysis of Energy and Exergy Calculation for Regenerator

Energy and exergy comparison is shown in Table 3.6. Some points can be found as follows:

- 1) Exergy efficiency ( $\epsilon_3 = 29\%$ ) is lower than energy efficiency ( $\eta_3 = 46\%$ ) while two different methods are used to study the same system.
- 2) Even though 16% energy loss (heat rejection) from regenerator seems to be a large portion, the 3% exergy loss indicates less availability associated with the loss. In another word 3% exergy loss indicates that one should spend less effort on focusing on recovering 3% exergy loss (or 16% energy loss) because the availability of the loss is limited. This is an example showing exergy value is a more practical tool in analysis of application .
- 3) The flue gas exergy is 31% exergy input to the device. This reminds to recover the availability.
- 4) 37% exergy destruction shows the irreversibility of heat transfer in regenerator.

The energy efficiency ( $\eta_3 = 46\%$ ) is lower than manufacturer's expectation in this time period of operation. The designed performances of burner and regenerator are better than the observed and



collected data from monitoring system. For instance, fuel combustion would take place at 1550K (vs. 1477K observed, i.e. 2330 °F vs. 2200 °F respectively), combustion air would be preheated to 1277K (vs. 750K observed, i.e. 1840 °F vs. 890 °F respectively) and flue gas (80% combustion gas) would exhaust at 450K (vs. 700K observed, i.e. 350 °F vs. 800 °F respectively). The best performed regenerator can preheat combustion air to 1390K (2040 °F). There are several reasons which may cause the discrepancies of design specification and observed parameters, for example, the regenerative system did not operate steadily after commissioning when this investigation and observation were conducted, the winter weather and rainy days also may influence preheated air temperature, furnace operators were not familiar with the new system, more unnecessarily frequent charging solid metal (ingot) may lower furnace temperature, etc. Analysis of energy and exergy distributions about furnace system from Tables 3.3, 3.4 and 3.5 are explained in next section.

## **3.2 Analysis and Assessment**

### **3.2.1 Flow Charts and Normalization**

Flow charts present energy and exergy distributions in systems. The width of flow is proportional to respective value of commodity. Rectangular frame presents furnace system as a whole. In order to assess regenerator performance, a small rectangular frame presents regenerator next to combustion chamber inside furnace system. Exergy destruction is shown as hatched area in exergy flow chart .

### **3.2.2 Comparison of Before Upgrade and After**

For illustrating an easy comparison, all energy/exergy values are normalized. The following Table 3.7 shows the normalized results that are based on Tables 3.3 and 3.4. For example, before upgrades, based on Tables 3.3, energy input before upgrades 21.40 TJ is normalized as 100%; so based on Tables 3.4, exergy input before upgrades 21.98 TJ is normalized as 103%. The discrepancy between 100 and 103 shows difference in energy and exergy of fuel when adopting two methods. The other values of energy and exergy are also normalized as shown in Tables 3.7. Adoption of energy and exergy methods to analyze the same process gives some different conclusions.

Table 3.7 Normalization of Energy and Exergy for Before Upgrades

Items	Energy		Exergy	
	(TJ)	%	(TJ)	%
<b>Input:</b>				
Natural gas	21.40	100	21.98	103
Combustion air	0		0	
Solid metal	0		0	
Total	21.40	100	21.98	103
<b>Output:</b>				
Stack flue gas	11.28	53	6.63	31
Melted metal	2.15	10	1.22	6
Loss from furnace	7.97	37	2.31	11
Total	21.40	100	10.16	48
Exergy destruction in furnace			11.82	55

1) Before Upgrades

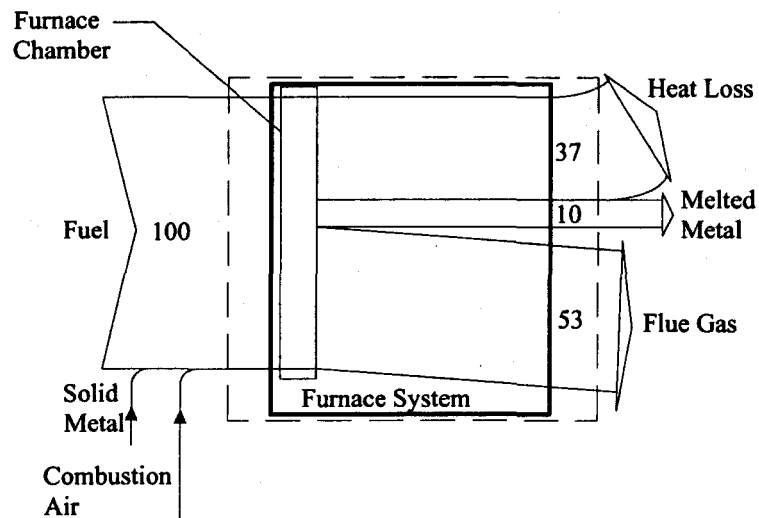


Figure 3.9 Energy flow chart before upgrades

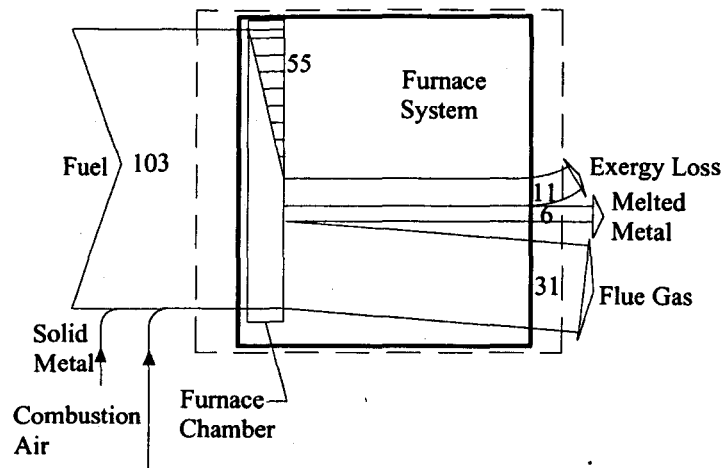


Figure 3.10 Exergy flow chart before upgrades (1)

Figures 3.9 and 3.10 are illustrating energy and exergy flows before upgrades based on Table 3.7. Some conclusions from reading flow charts are listed as follows:

- (1) Exergy destruction (55%) shown in hatched areas illustrates that exergy is not conserved. Combustion, melting and cooling processes are irreversible and cause exergy destruction.
- (2) In old system, without any control on exhaust flue gas, 53% energy associated with flue gas exhausted to environment. In view of exergy, actually 31% exergy associated with flue gas is emitted. This relatively large quantity (31%) exergy should not be considered "wasted", but should be considered availability to people. It reminds that 31% exergy should had been utilized. This is another example showing exergy value is practical and meaningful in application. It reminds users to focus on the material with more availability.
- (3) Exergy value sometimes is greater than energy value, at this circumstance,  $103\% > 100\%$ . Recall calculation results in section A.1, molar exergy input  $920,050 \text{ kJ}/(\text{kmol fuel})$  is slightly greater than molar energy input,  $895,761 \text{ kJ}/(\text{kmol fuel})$  in Tables A.1.10 and A.1.3A respectively.
- (4) In view of energy, 10% was transferred to product. The rest were released to plant and atmosphere through enclosure, stack and cooling system, i.e.  $90\% (=100-10)$  energy was

wasted. From Figure 3.10, 6% exergy transferred to product shows 42% (= 103-6-55) exergy was wasted. The both low efficiencies of 10% and 6% show potential benefit to upgrade those facilities. This was the subjective of the upgrading project.

## 2) After Upgrades

Based on Tables 3.3, energy input before upgrades 21.40 TJ again is normalized as 100%; refer to Table 3.8 below, input energy after upgrades 13.95 TJ is normalized as 74%; source natural gas energy input before upgrades 1 of 3.43 TJ is normalized as 63%.

Table 3.8 Normalization of Energy and Exergy Flows for After Upgrades

Items	Energy		Exergy	
	(TJ)	%	(TJ)	%
<b>Input:</b>				
Natural gas	13.43	63	13.95	65
Combustion air	0		0	
Solid metal	0		0	
Total	13.43	63	13.95	65
<b>Output:</b>				
Stack flue gas	3.25	15	1.73	8
Melted metal	2.15	10	1.22	6
Loss from furnace	7.23	34	2.1	9
Loss from regenerator	0.8	4	0.07	0.5
Total	13.43	63	5.12	23.5
<b>Exergy destruction</b>				
in furnace			7.56	35
in regenerator			1.2	6
in flue gas mixing			0.07	0.5
Total			8.83	41.5

The table shows 37% (=100-63) energy saving than before upgrades when maintaining same production, 10% energy on melting. Refer to Tables 3.8 for other normalized energy and exergy values, the following figures illustrate energy and exergy flows after upgrades.

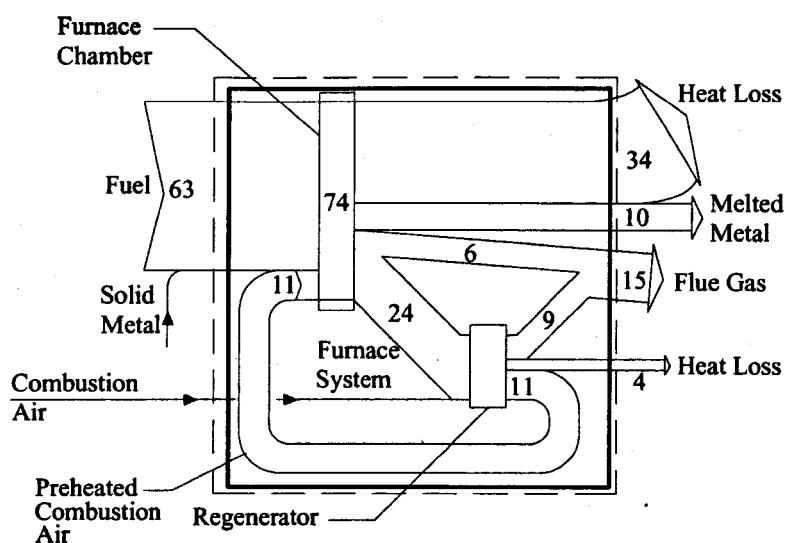


Figure 3.11 Energy flow chart after upgrades

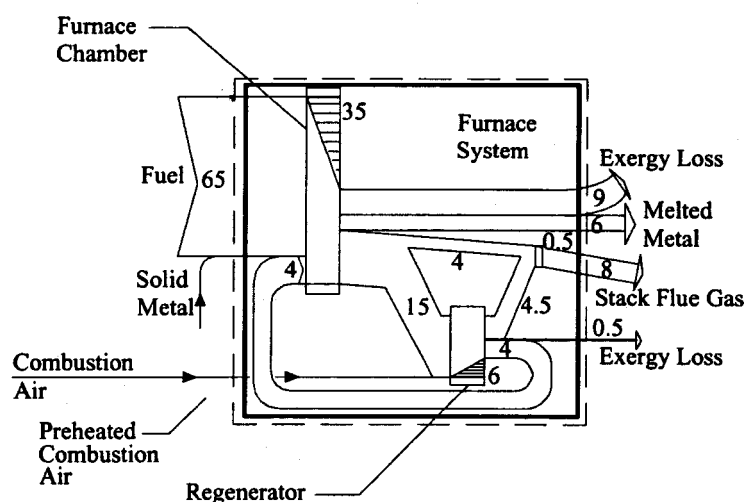


Figure 3.12 Exergy flow chart after upgrades (1)

Some points are addressed as follows:

- (1) Compare to previous source exergy input, 65% source exergy input shows 38% ( $=103\% - 65\%$ ) exergy saving as comparing to 100% energy input before upgrades.
- (2) Again, exergy value of fuel is greater than energy value, for after upgrades,  $65\% > 63\%$ . Like unit values (per kmol fuel) shown in sections A.1.2 and A.1.3, molar exergy input 1,054,609

$\text{kJ}/(\text{kmol fuel})$  is greater than molar energy input,  $895,761 \text{ kJ}/(\text{kmol fuel})$  in Table A.1.10 and A.1.3A respectively.

- (3) Energy loss (34%) from furnace chamber to environment reminds a possibility of utilizing heat loss from furnace, however exergy value 10% shows less availability of the loss. This again examples the benefit of using exergy value .
- (4) Comparing normalized 11% (2.38 TJ) energy recovery, only 4% (0.94 TJ) exergy recovery transferred to combustion air.

### 3.2.3 Comparisons of Energy Analysis and Exergy Analysis

Traditionally, energy method is used in efficiency analysis. Efficiency also may be evaluated by exergy flow charts. The values of energy and exergy are normalized here. Energy input (21.40 TJ) before upgrades is normalized as 100% in *energy analysis* when energy input (13.43 TJ) after upgrades is normalized as 63%; exergy input (21.98 TJ) before upgrades is also normalized as 100% in *exergy analysis* when exergy input (13.95 TJ) after upgrades is normalized as 64%. The other values are normalized based on Tables 3.3 and 3.4 and all results are summarized in Tables 3.9 and 3.10.

In this section, both of traditional energy method and current exergy method are used to evaluate changes of efficiencies of furnace and regenerator.

Table 3.9 Normalization of Energy Balances for Before and After Upgrades

Items	Before Upgrades		After Upgrades	
	(TJ)	%	(TJ)	%
<b>Energy Input:</b>				
Fuel natural gas	21.40	100	13.43	63
Combustion air	0		0	
Solid metal	0		0	
Total	21.40	100	13.43	63
<b>Energy output:</b>				
Stack flue gas	11.28	53	3.25	15
Melted metal	2.15	10	2.15	10
Energy loss in furnace	7.97	37	7.23	34
Energy loss in regenerator			0.8	4
Total	21.40	100	13.43	63

1) Energy method analysis

As the same normalizing rules applied, recall Figures 3.9 and 3.11 in previous sections and introduce here for convenient comparison.

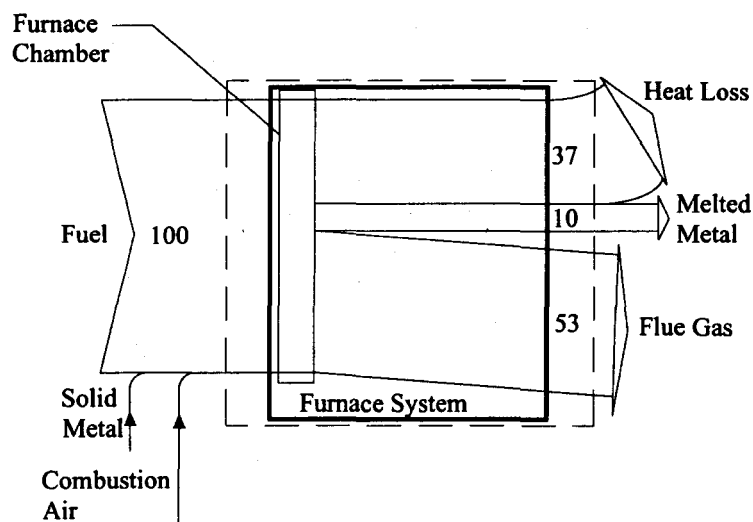


Figure 3.9 Energy flow chart before upgrades

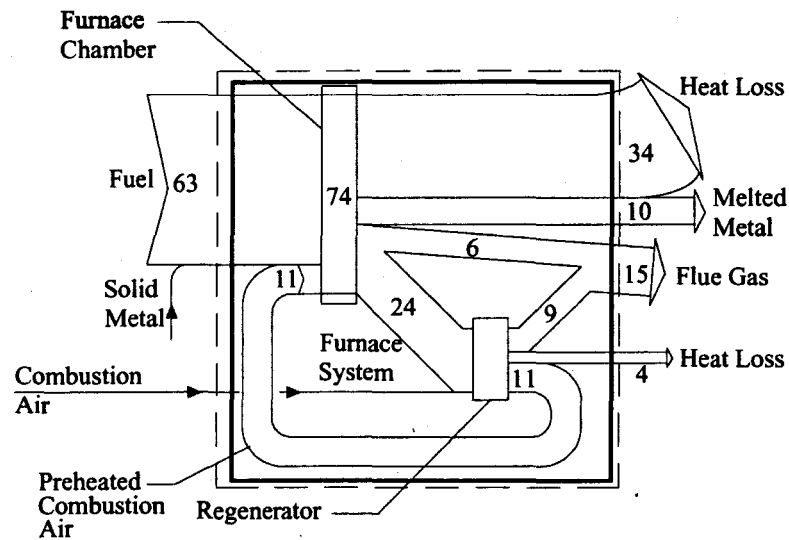


Figure 3.11 Energy flow chart after upgrades

Energy flow charts are shown as Figures 3.9 and 3.11 for before and after upgrades respectively. Some conclusions are explained from reading these figures.

- (1) Energy saving 37% ( $=100-63$ ) achieved when maintaining 10% energy for melting production in both charts. As shown in Table A.1.4, after upgrades, the new burner offers higher unit energy input (1,054,609 kJ/kmol fuel) than before (895,761 kJ/kmol fuel). This results from higher pressure of fuel supply ( $1.75 \times 10^5$  Pa vs.  $1.15 \times 10^5$  Pa) and better performances of system, such as higher combustion temperature etc.
- (2) After upgrades, 3% reduction of energy loss from furnace chamber (34%) is found less than before (37%).
- (3) 11% (2.38 TJ) energy transferred to combustion air reduced total energy input and fuel consumption. Refer to Table A.1.4, the regenerator improve unit enthalpy of reactant from (-76,700 kJ/kmol fuel) to (82,148 kJ/kmol fuel). The Figure 3.11 tells this type of regenerator can save 11% energy in similar systems.

## 2) Exergy method analysis



Subsequently, based on Tables 3.4, exergy input before upgrades 21.98 TJ now is normalized as 100%; refer to Table 3.10 below, input energy after upgrades 14.89 TJ is normalized as 68%; exergy flow charts are shown in Figures 3.13 and 3.14 for before and after upgrades respectively.

Table 3.10 Normalization of Exergy Balances for Before Upgrades and After

Items	Before Upgrades		After Upgrades	
	(TJ)	%	(TJ)	%
<b>Exergy Input:</b>				
Fuel natural gas	21.98	100	13.95	64
Thermomechanical exergy contribution	0.01	0.05	0.02	0.10
Chemical exergy contribution	21.97	99.95	13.93	63.9
Combustion air	0		0	
Solid Metal	0		0	
Total	21.98	100	13.95	64
<b>Exergy output:</b>				
Stack flue gas	6.63	30	1.73	8
Melted Metal	1.22	6	1.22	6
Exergy loss from furnace	2.31	11	2.1	9
Exergy loss from regenerator			0.07	0.5
Total	10.16	47	5.12	23.5
<b>Exergy destruction</b>				
in furnace	11.82	53	7.56	34
in regenerator			1.2	6
in flue gas mixing			0.07	0.5
Total	11.82	53	8.83	40.5

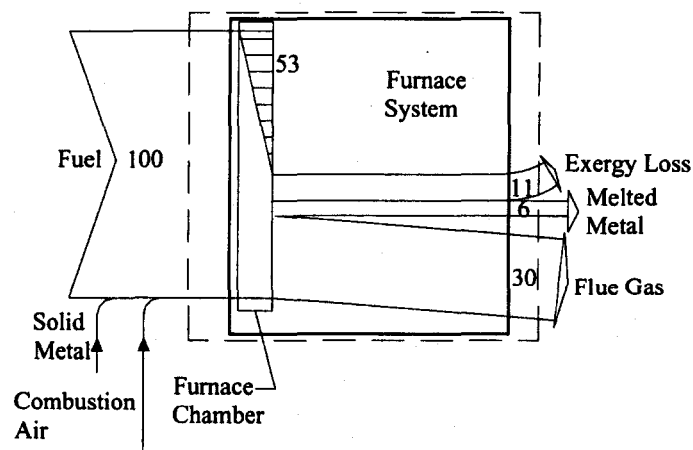


Figure 3.13 Exergy flow chart before upgrades (2)

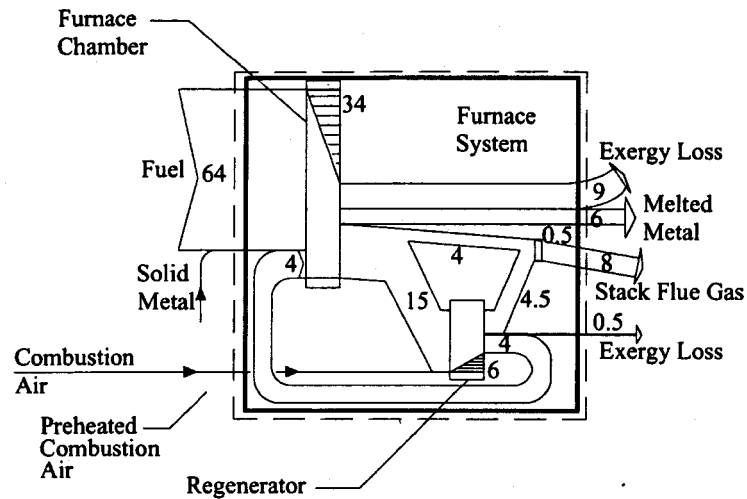


Figure 3.14 Exergy flow chart after upgrades (2)

Some conclusions are listed as below when reading two figures.

- (1) 36% exergy saving ( $=100-64$ ) is achieved when maintaining 6% exergy for production. Thermomechanical exergy contribution increased from 0.05% to 0.1% shows the benefit of higher gas pressure. This also can be referred to in Table A.1.10: unit thermomechanical exergy contribution are relatively small (322 kJ/kmol and 1291 kJ/kmol, for before and after upgrades respectively) when compare to chemical exergy contribution (919,728 kJ/kmol and 928,951 kJ/kmol, for before and after upgrades respectively). The improvement (0.1%) of unit chemical exergy (919,728 kJ/kmol fuel vs. 928,951 kJ/kmol fuel) is attained from better performance of gas burner, which consumes less oxygen, i.e. increasing logarithm part in

chemical exergy calculation equation:  $\bar{R}T_0 \ln\left(\frac{(y_{O_2}^e)^{n_{O_2}}}{(y_{CO_2}^e)^{n_{CO_2}} (y_{H_2O}^e)^{n_{H_2O}}}\right)$  in equation (A.12).

- (2) Waste exergy of flue gas at stack is greatly reduced from 30% to 8%.
- (3) Exergy loss from furnace slightly reduced from 11% to 9%. Compare to 4% exergy recovery, 0.5% exergy loss in regenerator appears relatively small (showing less availability).

- (4) 4% exergy is transferred to combustion air reduces total exergy input. This small number shows chemical exergy of preheated combustion air is zero because it is not related to temperature of preheated air.
- (5) Unused exergy is reduced from 94% (=100 – 6) to 58% (=64– 6). The 43% (=34+9) loss and destruction from furnace body show the possibility of recovery. The feasibility of the energy recovery will be addressed in next section .
- (6) In all above analysis, it is noticed that the thermomechanical exergy of solid metal ingot is zero, because ingot temperature is the same as of reference environment. If ingot temperature is to be increased before melting, total exergy input will be decreased and fuel consumption would be reduced more. This is discussed in further details in next section.

Stemmed from the above sections, the following two sections discussed about further cost saving and efficiency improvement: preheating ingot and utilization of waste from the system.

### 3.2.4 Preheating Ingot and Fuel Cost Saving

In this study, the 1,972,000 kg production of melted aluminium occurs during 52 working days in this plant. From section 3.1.3.3 energy comparison, after upgrades, heat rejection 21% (3.25 TJ) to the environment from stack flue gas in this time period; on the other hand, in exergy comparison, 12% waste exergy (1.73 TJ) of stack flue gas still shows the availability of the flow. If a preheating process were to use flue gas to warm up ingot, the waste of energy will be reduced, less energy will be consumed and efficiency of furnace will be improved. The follows examine the possibility of the proposal.

Firstly, if a device is designed to increase ingot temperature to 398 K (125 °C), which is 100 K above reference environment, the requested energy and exergy from equation (A.6) in A.1.3.1 and (A.14) in A.1.5.1 in Appendix A.1 respectively are

Energy consumption is the heat transfer to ingot :

$$\Delta Q = m c_i \Delta T = 1,972,000 \text{ kg} \times 0.903 \text{ kJ/kg.K} \times (398-298)\text{K} \times 10^{-9} \text{ TJ/kJ} = 0.18 \text{ TJ},$$

Change of exergy of ingot would only be the change of thermomechanical exergy contribution ,

$$\Delta A = \Delta A_{metal}^{tm} = \Delta Q - T_0 m c_1 \left[ \ln\left(\frac{T_f}{T_i}\right) \right] = 0.18 - 1,972,000 \times 298 \times 0.903 \times \ln(398/298) \times 10^{-9} \text{ TJ/kJ} = 0.02 \text{ TJ}$$

When the ingot preheating device were to be designed as the following efficiency, it is found the following table,

Table 3.11 Energy and Exergy Savings from Preheating Ingot

Items	Stack flue gas (TJ)	Designed Recovery efficiency (%)	Designed Recovery (TJ)	Designed Saving <sup>1</sup> (%)	Designed Fuel Saving <sup>2</sup> (%)
Energy	3.25	5.5	0.18	8.4	1.4
Exergy	1.73	1.2	0.02	1.6	0.1

Note:

- 1) the designed saving is the ratio of designed recovery to production energy and exergy consumption, 2.15 TJ and 1.22 TJ respectively.
- 2) the designed fuel saving is the ratio of designed recovery to total energy and exergy inputs, 13.43 TJ and 13.95 TJ respectively.

The table shows that to recover 5.5% energy (1.2% exergy) would preheat ingot up 100K and saving 1.4% energy (0.1% exergy). The follows evaluate financial feasibility of designed device.

The recent local price of natural gas supply is \$0.30/m<sup>3</sup> averagely in 2003, ECG, 2003. The estimated 5 year saving of fuel expense on the melting furnace is known as

$$\$0.30/\text{m}^3 \times 218,152\text{m}^3/52 \text{ days} \times 350 \text{ days/year} \times 1.4\% \times 5 \text{ years} = \$ 30,800$$

The estimation shows that if the cost of the designed device would be not more than \$30,800, and if the device would recover 5.5% energy or 1.2% exergy from flue gas so as to preheat ingot up to 398K (125°C), the device would reduce 1.4% fuel consumption and payback period would be 5 years, based on current fuel price.

The similar estimation can be made that if the cost of the designed device is not more than \$58,600, and if the device would recover 11% energy (4.6% exergy) from flue gas so as to preheat ingot up

to 498K (225°C), the device would reduce 2.7% fuel consumption and payback period would be 5 years.

To explore the feasibility of technology to preheat ingot economically is beyond the scope of this study and should be further investigated by others in future.

### 3.2.5 Cooling Water Utilization and Efficiency Improvement

From Table 3.3 in previous discussion (3.1.3.3), the energy loss from the furnace is evaluated at 7.23 TJ after upgrades, which is approximately 10% reduction from 7.97 TJ before upgrades. This 54% energy loss (in Table 3.3) is still considerably large. The following analysis assesses the loss and efficiency improvement.

The major part of the heat loss is the energy transferred to the environment through the furnace enclosure and to the cooling water system, which removes excessive heat from the furnace roof and walls in order to ensure the furnace body is not overheated. But the heated cooling water is not fully utilized usually. In winter, the water is supplied as a small part of a supplementary space heating source for the plant; the major space heating source is a group of gas-fired boilers; in summer, the water is cooled by cooling towers located on the roof and the return water is re-circulated to furnace. Should this part of lost energy/exergy be utilized, the overall furnace efficiency would be improved.

These calculation results approximately conform to an example in Table 7.5 in Szargut, 1988. After a similar melting furnace is examined, the results show that exergy loss is 17.5% of the exergy input. That exergy loss includes exergy associated with leaks from the furnace (17%) and with cooling water (0.5%). Since exergy loss in the cooling water is small, recovering cooling water exergy is not possible.

The utilization of lost energy/exergy could be used for space heating in the plant and office area, domestic water heating and even ingot preheating etc. The usage of energy /exergy loss relies on the parameters of the cooling water system. Because of lack of monitoring data and the limited

scope of this study, the technical and economical feasibilities of utilization of lost energy/exergy from the furnace should be researched by others in future.

If the entire furnace is not to be re-built, it is impossible to reduce or recover heat loss from furnace. The plant is very unlikely to demolish the furnaces and construct modern ones in near future.

### **3.2.6 Combustion Air Replacement and Efficiency Improvement**

The exergy of combustion air was zero before and after upgrades. To replace combustion air with pure oxygen will reduce fuel consumption. The “oxy-fuel” furnaces combusts fuel with pure oxygen. Because the combustion gas flow volume is five times smaller than that at a comparable air-blown furnace (Korobitsyn, 2002), the smaller flow reduces the amount of flue gases and waste heat. This type of furnaces can lead to energy savings of up to 20%. Pure oxygen is normally supplied as a liquid and is theoretically beneficial to the environment (Table 5 in Korobitsyn, 2002), but the high cost of pure oxygen trades off the advantages. The feasibility of pure oxygen is discussed elsewhere (Schalles, 1998).

### **3.3 Closure**

This chapter analyzes calculation results and illustrates energy and exergy distribution in the furnace system before and after upgrades. Some points are summarized as follows:

- 1) Both efficiencies of energy and exergy of the furnace are improved after upgrades. Furnace energy efficiency improved  $16\% - 10\% = 6\%$ , furnace exergy efficiency improved  $9\% - 6\% = 3\%$ .
- 2) Source energy and exergy consumptions are reduced with the same production maintained. 37% of energy and 36% of exergy savings are attained.
- 3) After upgrades, the new burner provides higher values of energy and exergy based on per mole of fuel.

- 4) The regenerating system shows 47% energy efficiency and 29% exergy efficiency.
- 5) The regenerator recovers 15% energy and 6% exergy.
- 6) Recovering heat from the stack flue gas to preheat the ingot is one of possibilities to further cost saving. Exergy associated with cooling water system shows energy of cooling water is less useful and not worth recovering in reality.

## CHAPTER 4

### ENVIRONMENTAL IMPACTS AND FINANCIAL ANALYSIS

This chapter evaluates environmental impacts and performs a basic financial analysis, based on calculation in the previous chapter.

#### 4.1 Environment Analysis

The first section presents the exergy-based insights into the environmental impact. Some suggest that exergy is a more insightful mean than conventional methods of examining environmental impact (Dincer and Rosen, Environment 1999), for not only is the quantity of exergy related to the state of the system itself, but is also related to the reference environment. Departure waste exergy could be zero only when the flow or substance is in equilibrium with the reference environment.

Zero waste exergy is not possible in this studied case, or in any hydrocarbon fuel combustion process. Flue gas always is associated with a greater amount of  $\text{CO}_2$  and  $\text{NO}_x$  than that in the environment that the flue gas enters. Even if a "perfect" heat exchanger were to be invented for a regenerator and 100% waste heat is recovered, the chemical exergy associated with  $\text{CO}_2$  and  $\text{NO}_x$  in flue gas would definitely form a potential impact on the environment. Exergy evaluation helps researchers to better determine environmental impact.

##### 4.1.1 Potential Impacts from Exergy Waste

The waste exergy of flue gas emissions represents a potential impact on the environment. The following discussions only use normalized energy or exergy values.

In a combustion process, natural gas becomes stack gases, causing a destruction of order in the environment while lesser exergy is associated with products of the process.

After upgrades, unused exergy of 4.08 TJ ( $=1.73+2.10+0.25$ ), excluding exergy destructions, refer to Table 3.4) is calculated at 28% of exergy input ( 16.64 TJ ) in 52 work days; annual exergy waste



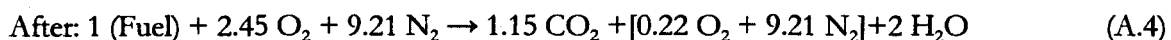
is then estimated at 27.5 TJ for 350 work days per year. This is equivalent to approximately 430,000m<sup>3</sup> natural gas wasted through the stack every year. These unconstrained emissions of exergy impact the environment in an uncontrolled manner. The exergy values of the stack flue gas show the ability of changing environment.

The melting process consumes a finite natural resource, natural gas. The combustion degrades natural gas because lower degraded energy is associated with the combustion product. Improved process efficiency can reduce this degradation without effect on production. In this study, the aim of the upgrade was to recover exhausted heat and to preheat combustion air.

#### 4.1.2 Nitrogen Oxides Emission Evaluation

Contaminants released from the furnace are combustion by-products and include nitrogen oxides (NO<sub>x</sub>), carbon dioxide (CO<sub>2</sub>) and water vapor. In many circumstances, some other chemical components such as sulphur dioxide (SO<sub>2</sub>), carbon monoxide (CO) and suspended particular matter (SPM), exist in the flue gas as well. Sulphur dioxide may result from alloy material. Sometimes carbon monoxide results from incomplete combustion. Because SO<sub>2</sub> and CO are a small portion of gross emission and also because this project's scope includes the study of regenerative technology, which focuses on reducing of nitrogen oxides (NO<sub>x</sub>) and carbon dioxide (CO<sub>2</sub>) emissions, the rest of combustion by-products (SO<sub>2</sub>, CO, SPM and flux emissions) are not considered in this discussion.

The following equations show that a small quantity of nitrogen and oxygen flow is involved in through the combustion process, when comparing before and after upgrades:



Further details and explanations for the above equations (3) and (4) can be found in section A.1.1 in Appendix A.1. As illustrated in section 2.3.5, staged combustion generates less nitrogen oxides, as shown in equations (A.3) and (A.4). When it is assumed that only NO<sub>2</sub> is generated in flue gas, the following are found:

Before upgrades:  $0.91 \text{ O}_2 + 11.8 \text{ N}_2 \rightarrow 0.45 \text{ NO}_2 + 11.69 \text{ N}_2$

After upgrades:  $0.22 \text{ O}_2 + 9.21 \text{ N}_2 \rightarrow 0.11 \text{ NO}_2 + 9.16 \text{ N}_2$

The left sides of equations are the same terms as the bracketed terms in equations (A.3) and (A.4) respectively. In reality, the mixture of both  $\text{NO}_2$  and  $\text{NO}$  is generated and can be expressed as in the following equations :

Before upgrades:  $0.91 \text{ O}_2 + 11.8 \text{ N}_2 \rightarrow 0.45 (a_1 \text{ NO}_2 + b_1 \text{ NO}) + 11.69 \text{ N}_2$  (4.1)

After upgrades:  $0.22 \text{ O}_2 + 9.21 \text{ N}_2 \rightarrow 0.11 (a_2 \text{ NO}_2 + b_2 \text{ NO}) + 9.16 \text{ N}_2$  (4.2)

From previous analysis, it is known that only 64% of the exergy is consumed after upgrades, i.e.

After upgrades,  $64\% (0.22 \text{ O}_2) + 64\% (9.21 \text{ N}_2) \rightarrow 64\% [0.11(a_2 \text{ NO}_2 + b_2 \text{ NO})] + 64\% (9.2 \text{ N}_2)$

This gives that, after upgrades, the reduction of  $\text{NO}_x$  emission as  $[1 - (64\% \times 0.11)/0.45] = 85\%$ . This is a good improvement on reduction of nitrogen oxides emission.

#### 4.1.3 Carbon Dioxide Emission Evaluation

It can be found in above equations (A.3) and (A.4) that  $\text{CO}_2$  is generated and emitted proportional to the amount of consumed hydrocarbon fuels. Regenerative technology does not directly reduce  $\text{CO}_2$  generation or emission, but  $\text{CO}_2$  emission reduction will be achieved when less fuel is consumed as expressed in the followings :

Before upgrades: 1 mole (Fuel) generates (1.15 moles  $\text{CO}_2$ )

After upgrades: 1 mole (Fuel) generates (1.15 moles  $\text{CO}_2$ )

Since it is known from above that 36% fuel saving is attained, 36% reduction of  $\text{CO}_2$  generation and emission is achieved by adopting new the burner technology and as result of regenerator program.

## 4.2 Financial Analysis

In this section, assessment of project investment is examined. The currency unit is the Canadian dollar.

### 4.2.1 Capital Investment

The overall project costs \$1.45 million to purchase and install three sets of regenerative burners. The plant invests \$120,000 on upgrading the natural gas supply system. The plant will receive \$68,000 in rebate from the local gas supplier when the project is fully implemented in all three furnaces. After upgrades, operation of the new burner system does not require an increased labour cost. The labour cost is neglected in this evaluation. Some other expenses are not considered in the study because they are under a maintenance budget, which occurs every year and does account for payback years.

The above capitals are invested for three furnaces. Since this study focuses on only one furnace, only one-third of the above investment and benefit is attributed to this assessment. The total capital input per furnace is :

$$[\$1,450,000 - \$68,000 + \$120,000] / 3 \approx \$501,000 \text{ per furnace.}$$

### 4.2.2 Fuel Cost Saving

From Table 3.1 and Table 3.2, the fuel saving is 296,540 m<sup>3</sup> (=514,692-218,152) when the same production maintained. The unit price of natural gas was approximately \$0.188/m<sup>3</sup> (in March, 2003, it became \$0.30/m<sup>3</sup>). This gives a total \$55,749 saving for 52 working days, or an average \$1,072 per day.

The actual average daily saving will be less than \$1072, because the selected 52 working days operated at full capacity, but in actual operation such as on Sunday, the furnace only operates in a holding mode and will not achieve the \$1,072 daily saving. From experiences of the plant personnel, approximately 25% working days are low production days, and low production only consumes 50% fuel of high production. These operation experiences give the fuel saving in 350 working days per year as:

$$\$1072 \times (350 \times 75\%) + (\$1072 \times 50\%) \times (350 \times 25\%) \approx \$330,000 \text{ /year furnace}$$

### 4.2.3 Payback Analysis

From the above estimations in sections 4.1.1 and 4.1.2, the simple payback period will be 18 months:

$$[\$501,000/\$330,000] \times 12 \text{ months/year} \approx 18 \text{ months.}$$

Further analysis is broken-down as follows:

- 1) Burner maintenance cost is excluded. Approximately every 6 months, regenerators need to be cleaned in order to remove clogging and to reduce resistance when gases flow through. Cost of material (media) in regenerators and cost of labour are unanticipated.
- 2) During regenerator maintenance, the regenerative system will be switched to the conventional mode. Therefore no combustion air will be preheated, and this operation mode will decrease expected fuel cost saving .
- 3) Some merits on environmental issues are not undertaken in the payback analysis, such as the fact that flue gas temperature has been reduced, NO<sub>x</sub> and CO<sub>2</sub> emission has been decreased, potential environment impacts are less than previous. In a detailed financial analysis, these factors should be considered .

### 4.2.4 Discussion

Some research papers (NCCIT, 1998) explained typical barriers to the implementation of emission reduction technologies in the transportation manufacturing sector, such as the relatively long payback period (greater than 2 years), are disadvantages in the competition for capital, and higher operating costs associated with increasing energy prices will reduce the competitiveness of the Canadian industry, etc.

In this study, an approximate 18 months payback period is shorter than usual expectation of 24 months, and regenerative burner system operates with well designed PLC control and thus does

not require extra operating cost. In the selected plant, for one furnace, the average \$501,000 investment versus \$323,000 fuel saving per annum is a worthwhile decision and the project meets initial objectives.

In the upgraded natural gas distribution system (including new pressure regulating valves), the total of \$120,000 was invested for increasing fuel supply pressure. It is helpful to increase energy and exergy per mole of natural gas and increase total inputs of energy and exergy.

#### **4.2.5 Exergy Costing Analysis**

Financial assessment can be carried out in several ways. The exergy approach is a practical tool to discuss worthwhile (or not) investment in thermal engineering projects, as exergy values present the availabilities of streams in a system and exergy loss shows the waste of resources, i.e., waste of investment. Some researchers studied a thermoeconomic approach with the exergy method (Pehler, 1983) and found that, by using exergy (availability) values to exam a system, the method gives very close conclusions and accurate suggestions. Sometimes the ratio of exergy loss to capital cost is a direct parameter to analyze a thermal system (Rosen 1986).

An exergy-costing investigation is beyond the scope of this study scope; also, to gather detailed financial information on the project and detailed operation cost is not objective of this study. Thus the exergy costing method is not employed in the financial analysis in this study.

## CHAPTER 5

### CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the accomplishments and findings of the study. Conclusions and recommendations for further study are given.

#### 5.1. Summary of Accomplishments

The study conducted background investigations of the die casting industry and aluminium melting process, while addressing environmental issues and the capital investment in the industry and process. This report carried out a literature review of exergy methodology, comparison of energy and exergy methods and applications of exergy theory. The report introduced regenerative technology and detailed system operation after communicating with the manufacturer and understanding product information. System efficiency and emission are calculated based on the energy and exergy methodology while illustrating efficiency analysis and considerations. Analysis was made to assess the environmental impact and evaluate exhaust emission and pollutants. A financial analysis predicts a payback period of 18 months.

#### 5.2. Summary of Findings

The study found the following relating to the exergy method and thermal technology.

- 1) The calculations show the benefits of using exergy values. The first example in Table 3.4, before upgrades, shows that 30% of the total exergy input associated with flue gas should be considered available for use and should have been utilized. In the second example in Table 3.8, after upgrades, the energy loss of 34% (of total energy input) from furnace chamber to environment indicates a possibility of utilizing the loss, however the exergy value 9% shows less availability of the loss. In the third example in Table 3.6, in the regenerator, a relatively large exergy destruction (37% of exergy input to regenerator) indicates it may be better to improve heat transfer performance of the regenerator instead

of to improve insulation of the regenerator. The heat transfer performance of regenerator includes the heat transfer between combustion gas and media and heat transfer between media and combustion air.

- 2) The overall system energy efficiency increases from 10% to 16% and the system exergy efficiency increases from 6% to 9%, when the same production is maintained.  $(\bar{h}_p - \bar{h}_R)$ , the unit heat transfer from combustion based on per mole of fuel, is greatly improved from 423,476 kJ/kmol to 625,501 kJ/kmol due to the higher temperature of POC, better controlled A/F rate and higher temperature of reactant air. The unit thermomechanical exergy of natural gas is increased from 322 kJ/kmol to 1291 kJ/kmol by increased gas pressure. The chemical contribution is improved approximately 1%, from 919,728 kJ/kmol to 928,951 kJ/kmol.
- 3) 36% exergy saving and 37% energy saving of fuel consumption are mainly obtained from the regenerative burner system with the same production. The payback period for the whole system is approximate 18 months.
- 4) After upgrades, the emission of nitrogen oxides ( $\text{NO}_2$  and  $\text{NO}$ ) is reduced by 85% and  $\text{CO}_2$  emission is reduced by 37%.
- 5) After upgrades, heat rejection 3.25 TJ to the environment from the stack flue gas is significantly less than 11.28 TJ before upgrades. The reduction of waste exergy emission decreased from 6.63 TJ to 1.73 TJ. Both reductions decrease the thermal impact on the environment.
- 6) Before upgrades, the total unused energy in the system is 90%; after upgrades, the total unused energy in the system is reduced to 72%; current 9.66 TJ exergy loss and destruction from the furnace chamber is less than before (14.13 TJ). These show the overall furnace system performance is improved.

- 7) The gas combustion, melting and water-cooling processes inside the furnace chamber destroy more than 50% of exergy input before and after upgrades. This is the largest exergy waste in the system.
- 8) The exergy value sometimes is greater than energy value, such as in this calculation. The molar exergy input 920,050 kJ/(kmol fuel) is slightly greater than the molar energy input, 895,761 kJ/(kmol fuel).
- 9) Before and after upgrades, both energy and exergy inputs of solid metal (aluminium ingot including scraps) are zero. If a device were designed to recover 5.5% energy or 1.2% exergy from the current flue gas so as to preheat the ingot up to 398K (125°C), the device would reduce 1.4% fuel consumption and the payback period would be 5 years only when the device costs less than \$30,800; if one expects the device to recover 11% energy (4.6% exergy) from current stack flue gas so as to preheat the ingot up to 498K (225°C), the device would save 2.7% fuel consumption and the payback period would be 5 years only when the cost of the device is not more than \$58,600, based on current fuel price.
- 10) In the regenerator, exergy efficiency ( $\epsilon_3 = 29\%$ ) is lower than energy efficiency ( $\eta_3 = 46\%$ ) when two different methods are used to study the same system. Exergy destruction in the regenerator is 37% of the total exergy input to the regenerator. Miscellaneous exergy loss in the regenerator is less than 3% which indicates the availability of the loss is limited even though 16% of the total energy associated with the loss.

### 5.3. Conclusions

- 1) Exergy is a more practical tool compared to the conventional energy method when examining the thermal performance of the same melting furnace and the same regenerator.
- 2) Implementing regenerative technology results in enhanced system performance indicated by an exergy efficiency improvement. Staged burner and regenerator benefits meet the targets of design. The environmental friendly regenerative burner system improves efficiency, lowers NOx emission, achieves fuel saving and provides quick financial payback.



- 3) The thermomechanical exergy contribution of natural gas is a smaller portion of total exergy comparing to the chemical exergy contribution, which is more important to natural gas.
- 4) Preheating combustion air helps to improve furnace efficiency. The recovered energy and exergy save fuel consumption in furnace.
- 5) The stack flue gas exergy (1.73 TJ) still shows the availability. Preheating the ingot will increase the total exergy input to system. If a preheating device were to recover heat from the stack flue gas to warm up the ingot, the waste of energy and exergy will be reduced, less fuel will be consumed and the efficiency of furnace will be improved.

#### **5.4. Recommendations**

The recommendations below follow from this study:

- 1) The exergy methodology should be extended to analyze a wider range of industrial and engineering problems.
- 2) More regenerative technologies should be considered in similar applications. Regenerative burner systems have been commercially available for use on aluminium melting furnaces for many years. There are many melting furnaces in North America equipped with regenerative combustion systems. The furnaces successfully keep NO<sub>x</sub> generation below the regulated level while attaining increases in heating capacity. Despite the proven benefits of high fuel efficiency and high productivity, many plants remain reluctant to adopt this technology, Schalles, 2002. Since environmental regulations are likely to become more severe in the future, all furnaces should be forced to adopt the regenerative burner system.
- 3) In future exergy calculation, the thermomechanical exergy contribution of natural gas can be neglected when natural gas is supplied at the same temperature of environment, even though it is compressed to 170 kPa (10 psi).

- 4) To recover heat from the stack flue gas and preheat the ingot is recommended, as it directly reduces waste while saving fuel when the device design is economically possible.

## REFERENCES

- Aprea, 2003: C. Aprea, F. de Rossi, A. Greco and C. Renno, Refrigeration Plant Exergetic Analysis Varying The Compressor Capacity, *International Journal Of Energy Research*, 2003; 27:653–669
- Bejan, 1988: Bejan A., *Advanced Engineering thermodynamics*. Wiley: New York, 1988.
- Bejan, 1996: Bejan A., Tsatsaromis G, Moran M.. *Thermal Design and Optimisation*. Wiley: New York, 1996.
- Bisio 2000: G. Bisio, G. Rubatto, R. Martini, Heat Transfer, Energy Saving And Pollution Control In UHP Electric-Arc Furnaces, *Energy* 25 (2000) 1047–1066
- Bilal, 2003: Bilal A. Qureshi and Syed M. Zubair, Application Of Exergy Analysis To Various Psychrometric Processes, *International Journal Of Energy Research*, 2003; 27:1079–1094
- Bayrak, 2003: Mustafa Bayrak, Adnan Midilli and Kemal Nurveren, Energy And Exergy Analyses Of Sugar Production Stages, *International Journal Of Energy Research* 2003; 27:989–1001
- Camdali and Tunc, 2001: Unal Camdali, Murat Tunc, Feridun Dike, A Thermodynamic Analysis of a Steel Production Step Carried Out in the Ladle Furnace, *Applied Thermal Engineering* 21 (2001) 643-655, Elsevier, 2001
- Cengel and Boles, 1998: Yunus A. Cengel, Micheal A. Boles, *Thermodynamics An Engineering Approach*, 3<sup>rd</sup> Edition, McGraw-Hill, 1998
- Cownden, 2000: Ryan Cownden, Meyer Nahon, Marc Rosen, *Exergy Analysis of a Fuel Cell Power System for Transportation Applications*, 2000,
- Dincer and Rosen, 2001: Ibrahim Dincer, Marc Rosen, Energetic, Environmental and Economic Aspects of Thermal Energy Storage Systems for Cooling Capacity, *Applied Thermal Engineering* 21, 2001, 1105-1117.
- Dincer and Rosen, Environment 1999: Ibrahim Dincer, Marc Rosen, The Intimate Connection between Exergy and the Environment. in *Thermodynamic Optimization of Complex Energy Systems*, Kluwer Academic, Netherlands, 221-230, 1999.
- Dincer and Rosen, Thermal Storage 1999: Ibrahim Dincer, Marc Rosen, Thermal Storage and Exergy Analysis: the Impact of Stratification, *Transactions of the CSME* 23(1B), 173-186, 1999
- Direct Energy, 2003: Figure 1.1 Data and chart from <http://www.directenergy.com>, browsed at March, 2003.

- ECG, 2003: Enbridge Consumer Gas Company, Material Safety Data Sheet, <http://www.egd.enbridge.com/B/brochures.asp>, browsed at Feb 15, 2003
- Etele and Rosen, 2001: Jason Etele, Marc Rosen, Sensitivity of Exergy Efficiencies of Aerospace Engines to Reference Environment Selection, *Exergy-An International Journal*, 1(2) 2001, Elsevier
- Energysshop, 2003: Figure 1.2 data from <http://www.energysshop.com>, browsed at March 25, 2003.
- Flamme, 2002: Michael Flamme, Gaswärme-Institut e.V. Essen, Germany Second International Seminar on High Temperature Air Combustion, Sweden, 2002, <http://www.metallurgi.kth.se/htc/skiva/presentations/flamme.pdf>, browsed at Jan 30, 2002.
- Gas Handbook, 1966: Gas Engineers Handbook, The Industrial Press, 1966
- Ghaddar 2003, Nesreen Ghaddar, Kamel Ghali and Antoine Najm, Use Of Desiccant Dehumidification To Improve Energy Utilization in Air-Conditioning Systems in Beirut, *International Journal Of Energy Research*, 2003; 27: 1317-1338
- Guthrie, 1999: Brad Guthrie, Bob Link, In Reduction of Plant Emissions with High Efficiency, Low NOx Melting Design, North American Die Casting Association, 1999, Cleveland T99-091.
- Ionita, 2002: Ion C. Ionita, Engineering And Economic Optimization Of Energy Production. *International Journal Of Energy Research*, 2002; 26: 697 - 715
- IEC, 1998: Sustainable Industry: Metal Casting Industry Profile, by: Industrial Economics, Inc. [http://www.resourcesaver.com/file/sectorstar/program\\_63.pdf](http://www.resourcesaver.com/file/sectorstar/program_63.pdf), browsed at Jan 30, 2003.
- Kawasaki, 2000: Environmental Report 2000, Kawasaki Steel Corporation, [http://www.kawasaki-steel.co.jp/kankyo\\_e/2000e.pdf](http://www.kawasaki-steel.co.jp/kankyo_e/2000e.pdf).
- Kanicki, and Kirgin, 1996: David Kanicki and Kenneth Kirgin, Nonferrous Foundries Vie for Continued Growth" *Modern Casting*, September 1996.
- Korobitsyn, 2002: Mikhail Korobitsyn, Industrial Applications Of The Air Bottoming Cycle, *Energy Conversion and Management* 43 (2002) 1311-1322
- Moran and Shapiro, 1995: Michael Moran and Howard Shapiro, *Fundamentals of Engineering Thermodynamics*, 3<sup>rd</sup> Edition, John Wiley & Sons, Inc., 1995
- NADCA, 1996: EPA Office of Compliance Sector Notebook Project: Profile of the Metal Casting Industry, February 1998, Office of Compliance, Office of Enforcement and Compliance Assurance, U.S. Environmental Protection Agency, <http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/metcastsna.pdf>, browsed at Jan 10, 2003

- NCCIT, 1998: National Climate Change Industry Table, Canada, Foundation Paper for the Transportation Equipment Manufacturing Sector, The Transportation Equipment Manufacturing Sector Working Group, 1998
- Pehler, 1983: F.A. Pehler, Y.A. Liu, Thermodynamic Availability Analysis in the Synthesis of Optimum-Energy and Minimum-Cost Heat Exchanger Network, 0091-6151/83/0235-0161, American Chemical Society, 1983
- Petela, 2002: R. Petela, W. Hutnyb, J.T. Price, Energy and exergy consumption and CO<sub>2</sub> emissions in an ironmaking process, *Advances in Environmental Research* 6 (2002), Elsevier
- Ratts, 2000: Eric B. Ratts, J. Steven Brown, An Experimental Analysis Of Cycling In An Automotive Air Conditioning System. *Applied Thermal Engineering* 20 (2000) 1039±1058
- Rosen, 1986: Marc Rosen, The Development and Application of a Process Analysis Methodology and Code Based on Exergy, Cost, Energy and Mass, PhD thesis, 1986.
- Rosen and Dincer, 1997: Marc A. Rosen and Ibrahim Dincer, On Exergy and Environmental Impact, *International Journal of Energy Research*, Vol. 21, 643–654, 1997;
- Rosen, 2001: Marc A. Rosen, The Exergy Of Stratified Thermal Energy Storage, *Solar Energy* Vol. 71, No. 3, pp. 173-185, Elsevier, 2001
- Rosen and Dincer, 2001: Marc Rosen and Ibrahim Dincer, Exergy as the Confluence of Energy, Environment and Sustainable Development,. *Exergy International Journey* 1(1) (2001) 3–13)
- Rosen, Building Systems 2001: Marc Rosen, Wey Leong, Minh N. Le, Modeling and Analysis of Building Systems that Integrate Cogeneration and District Heating and Cooling, The Canadian Conference on Building Energy Simulation, 2001, <http://www.esim.ca/2001/document/proceedings/session5-4.pdf> (browsed on Jan 31, 2003)
- Rosen, 2002; Marc A. Rosen, Can Exergy Help Us Understand and Address Environmental Concerns? Exergy, *An International Journal* 2, 2002 214–217.)
- Schalles, 2002: David G. Schalles, The Next Generation of Combustion Technology for Aluminium Melting, Cast Shop Technology Conference Paper, The Minerals, Metals and Material Society, February 1998.
- Sagian, 2003: A. Stegou-Sagian and N. Pagnigiannis, Exergy Losses In Refrigerating Systems. A Study For Performance Comparisons In Compressor And Condenser, *International Journal Of Energy Research*, 2003; 27:1067–1078
- S. De, 2003: S. De, D. Roy and A. Sarkar. Performance Study Of A Partial Gasification Pressurized Combustion Topping Gas Cycle And Split Rankine Combined Cycle: Part II - Exergy Analysis. *International Journal Of Energy Research* 2003; 27:561–574

- Silveira, 2002: J. Luz-Silveira, A. Beyene, E.M. Leal, J.A. Santana, D. Okada, Thermoeconomic analysis of a cogeneration system of a university campus *Applied Thermal Engineering* 22 (2002) 1471–1483
- Struchtrup and Rosen, 2002: H. Struchtrup, M Rosen, How Much Work Is Lost in Irreversible Turbine, *Exergy-An International Journal*, 2(3), 152-158 (2002)
- Shiramizu, 2001: Kousuke Shiramizu, Steadily Meeting Voluntary Goals and Reducing Environmental Impact, Toyota, 2001, [http://www.toyota.co.jp/IRweb/corp\\_info/envrep/envrep00/pdf/c40\\_51.pdf](http://www.toyota.co.jp/IRweb/corp_info/envrep/envrep00/pdf/c40_51.pdf)
- Szargut, 1988: Jan Szargut, David Morris, Frank Steward, *Exergy Analysis of Thermal, Chemical and Metallurgical Process*
- Verkhivkera and Yantovskib, 2001: G. Verkhivkera, E. Yantovskib, Zero-emissions Gas-fired Cogeneration of Power and Hydrogen, International Association for Hydrogen Energy, *International Journal of Hydrogen Energy* 26 (2001) 1109-1113, Elsevier, 2001
- Virtanen, 2002: Markku Virtanen, *Energy Conservation in Buildings and Community Systems*, Technical Report, Finland, 2002
- Winter and Nitsch, 1990: Winter C-J, Nitsch J., *Hydrogen as An Energy Carrier. Technologies, Systems, Economy*, Berlin, Springer, 1990
- Zheng, 2001: D. Zheng, P. Ji and J. Qi, Maximum Excess Gibbs Function Of Working Pairs And Absorption Cycle Performance, *International Journal of Refrigeration* 24 (2001) 834-840

## GLOSSARY OF TERMINOLOGY

**Availability:** is also called Available Energy or Exergy, see Exergy

**Chemical Exergy:** is equal to maximum work obtainable when the substance under consideration is brought from the environmental state to the dead state by process involving heat transfer and exchange of substance only with the environment (Kotas, 1995)

**Exergy:** is the maximum work potential of a given form of energy within the reference environment. (Kotas, 1995)

**Exergy destruction:** is a phenomenon of loss of work potential of a system which take place during an irreversible process (Kotas, 1995)

**Hot metal:** is melted liquid metal that is charged to melting furnace for keeping furnace temperature and occupancy, also called hot charge

**Ingot:** is raw material for melting process, aluminium alloy in this study, also called ingot rack, bar, etc.

**Molten:** is liquid melted metal that is ready for casting

**Regenerator:** is a heat exchanger to reclaim heat associated with flue gas and to preheat combustion reactants

**Regenerative burner:** is a set of system that combined with regenerator and burners that is designed to reduce nitrogen oxides emission

**Scrap:** is recycled unqualified product or scrap trimmed from qualified product after casting process

**Thermomechanical Exergy:** is the exergy associated with a heat interaction. (Kotas, 1995)

## APPENDICES

### APPENDIX A.1

#### Energy and Exergy Calculations

The calculations are based on theory and equations in Moran and Shapiro, 1995. All source values of enthalpy, entropy and other properties of various types of gases are taken from the same book, unless otherwise noted.

The following assumptions are made in the study:

- 1) The reference environment temperature  $T_0$  is taken to be 25°C; the reference environment pressure  $p_0$  is taken to be 1 atm. The annual average temperature is 7.2°C in Toronto, Canada. In cold weather, the actual system efficiency will be lower than the calculated in this study; on the other hand, utilizing cooling water in space heating system increases overall system efficiency. For simplicity, average temperature 25°C is used in this study.
- 2) The system within the control volumes indicated on Figures 3.1 and 3.2 by a dashed frame operates at steady state. Also  $W_{cv}=0$ .
- 3) Each mole of  $O_2$  in the combustion air is accompanied by 3.76 moles of  $N_2$ .
- 4) The fuel and combustion products are treated as an ideal gas mixture.
- 5) All product of combustion exit furnace chamber and exhaust through stack . Some combustion gas or the flue gas leaked from furnace door and flue duct are not considered in mass balance this study . In actual operation a slight positive pressure is maintained in furnace in order to prevent outside cold air from entering furnace. But air leaked from furnace door to outside is small quantity when comparing to combustion



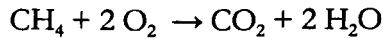
gas exiting furnace chamber. Therefore the combustion gas leaked from furnace door is ignored. It is assumed that all flue gas (or combustion gas after upgrades) exits furnace chamber.

- 6) The kinetic and potential energy effects are negligible.
- 7) The electricity consumption is not considered in energy and exergy input to system since the expense of power is small as comparing fuel expense. The electricity is consumed on various types of motor and devices in monitoring system and control system. By far no power record is metered particularly for furnace system, either for before and after upgrades; however, in the plant, monthly electricity bill related to production is usually only few percentage of natural gas bill. Therefore to neglect electricity consumption does not affect overall energy efficiency significantly.
- 8) In composition of natural gas supplied by local gas vender also includes nitrogen ( $N_2$ ), carbon dioxide ( $CO_2$ ), hydrogen sulphide ( $H_2S$ ) and water vapor ( $H_2O$ ), from ECG 2003. hydrogen sulphide ( $H_2S$ ) is added for safety concerns. Since volumes of  $N_2$ ,  $CO_2$ ,  $H_2S$  and water vapor ( $H_2O$ ) are very small so they are neglected in this calculation, and their molar fractions are not considered in natural gas composition.
- 9) The studied time period is from December 2002 to March 2003, there are total 96 working days, but 43 working days were not in full capacity of production due to maintenance and holidays shutdown. The production data and fuel consumption are taken from the rest of 53 working days.

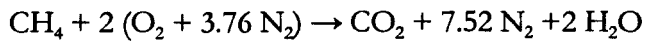
Source data collected from plant and recorded from furnace operation are summarized in Tables 3.1 and 3.2.

#### **A.1.1 Chemical Equation**

The chemical equation for the complete combustion of methane is



Considering the above assumption 3) at start of Appendix A.1, combustion air which supplies  $\text{O}_2$  are taken from environment, above equation becomes

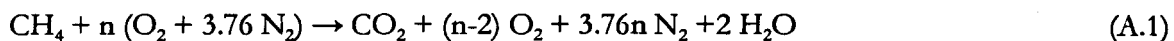


On a molar basis, the air-fuel ratio is

$$(\text{A}/\text{F})_{\text{theo}} = (2 / 1) \times 4.76 = 9.52$$

In actual furnace operation, A/F is always higher than  $(\text{A}/\text{F})_{\text{theo}}$ .

Before upgrades, A/F ratio was controlled by furnace operators observing flame color. After upgrades, regenerative burner's PLC control system adjusts the actual air-fuel ratio mainly based on furnace temperature. The actual chemical equation becomes

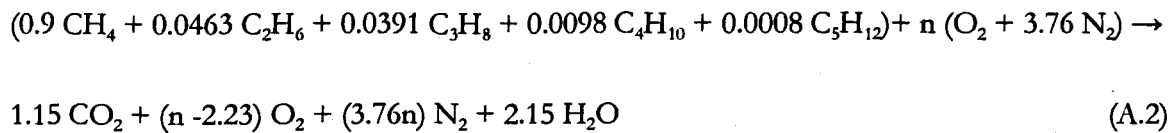


Natural gas supplied is not pure methane ( $\text{CH}_4$ ). The natural gas composition is shown in Table A.1.1, where values have been taken from Gas Handbook, 1966. The molar enthalpy and Gibbs function of formation at reference environment of fuel natural gas is calculated in the following table.

Table A.1.1 Natural Gas Composition

Substance	Chemical Form	Mole Fraction	$\bar{h}_f^0$ (fuel) (kJ/kmol)	$\bar{g}_f^0$ (fuel) (kJ/kmol)
Methane	$\text{CH}_4$	0.90	-67,365	-50,790
Ethane	$\text{C}_2\text{H}_6$	0.0463	-3,921	-32,890
Propane	$\text{C}_3\text{H}_8$	0.0391	-4,061	-23,490
Butane	$\text{C}_4\text{H}_{10}$	0.0098	-1,236	-15,710
Pentane	$\text{C}_5\text{H}_{12}$	0.0008	-117	-8,200
Natural Gas		1.0	-76,700	-48,313

To introduce natural gas composition to equation (A.1):



In the following discussions,  $n_1$  and  $n_2$  are defined as coefficients in equation (A.2) for before upgrades and after upgrades, respectively.

Before upgrades, stack testing (on wet basis) on furnace was conducted by plant, 6%  $\text{O}_2$  in volume of emission was found in flue gas exhaust. According to equation (A.2)

$$(n_1 - 2.23) / [1.15 + (n_1 - 2.23) + 3.76n_1 + 2.15] = 6 \%$$

Thus  $n_1 = 3.14$  makes equation (A.2) balanced. Thus, before upgrading project, chemical equation is

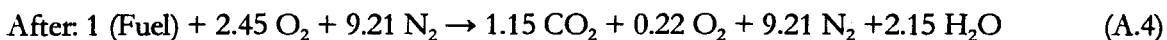


The underlined short term in equation (A.3) is used to present fuel natural gas composition in equation (A.2). This short term will be used in the study. Then, ratio  $(A/F)_1 = (3.14 / 1) \times 4.76 = 14.95$

After upgrades, the regenerative burner's emission analysis is based on lab testing for this type of burner. The testing was carried out in manufacturer's lab, Bloom Engineering. 1.74%  $\text{O}_2$  is found in flue gas. From equation (A.2), it gives:

$$(n_2 - 2.23) / [1.15 + (n_2 - 2.23) + 3.76n_2 + 2.15] = 1.74 \%$$

so  $n_2 = 2.45$  and the equation (A.2) is balanced. Thus, after upgrading project, chemical equation is



Then, ratio  $(A/F)_2 = (2.45/1) \times 4.76 = 11.66$ . Equation (A.3) and (A.4) are used in the rest of calculation. Each coefficient ( $n_i$ ) shown in the following equations in the Appendix is the same as the corresponding respective coefficient of the chemical equation (A.3) and (A.4).

### A.1.2 Energy Input to Furnace System

The chemical reaction (fuel combustion) generates the majority of energy input. It must be noted that another part of energy input is the energy associated with combustion air (and with preheated combustion air after upgrades). The two parts are calculated separately as following.

#### A.1.2.1 Energy balance of combustion

Since fuel and air enter combustion chamber separately, the following figure illustrates the combustion for the following calculation.

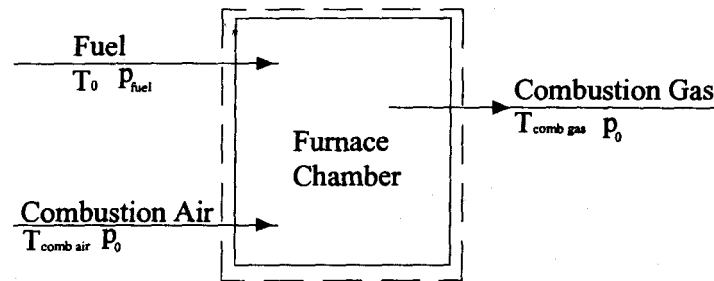


Figure A.1.1 Schematic of energy calculation of fuel combustion

The lower heating value (LHV),  $\bar{h}_{RP}^0$ , is used here for calculating energy input of combustion.

$$\bar{h}_{RP}^0 \text{ (kJ/kmol fuel)} = \sum_P n_e (\bar{h}_f^0)_e - \sum_R n_i (\bar{h}_f^0)_i \quad (\text{A.5})$$

$$\text{where } \sum_P n_e (\bar{h}_f^0)_e = n_{\text{CO}_2} (\bar{h}_f^0)_{\text{CO}_2} + n_{\text{O}_2} (\bar{h}_f^0)_{\text{O}_2} + n_{\text{N}_2} (\bar{h}_f^0)_{\text{N}_2} + n_{\text{H}_2\text{O}} (\bar{h}_f^0)_{\text{H}_2\text{O}}$$

$$\text{and } \sum_R n_i (\bar{h}_f^0)_i = n_{\text{Fuel}} (\bar{h}_f^0)_{\text{Fuel}} + n_{\text{O}_2} (\bar{h}_f^0)_{\text{O}_2} + n_{\text{N}_2} (\bar{h}_f^0)_{\text{N}_2} = (\bar{h}_f^0)_{\text{Fuel}}$$

The values of enthalpy of formation of the component at reference environment are on basis of per kmole fuel. Energy input of combustion from natural source fuel can be expressed as:

$$E_{\text{fuel}} = n_{(\text{Fuel})} \bar{h}_{RP}^0$$

$n_{(\text{Fuel})}$  denotes total moles of fuel consumed. With enthalpy of formation values from Tables A-24 in Moran and Shapiro, 1995, calculation results are tabulated in Table A.1.2,

Table A.1.2 Calculation of Energy Input to Furnace Chamber

Items	Before upgrades	After upgrades
$\sum_P n_e (h_f^0)_e$ (kJ/kmol fuel)	-972,461	-972,461
$\sum_R n_i (h_f^0)_i = (\bar{h}_f^0)_{\text{Fuel}}$ (kJ/kmol)	-76,700	-76,700
$\bar{h}_{RP}^0$ (kJ/kmol fuel)	-895,761	-895,761
$n_{(\text{Fuel})}$ (kmol)	23,890	14,993
$E_{\text{fuel}} = E_{\text{source}} = n_{(\text{Fuel})} \bar{h}_{RP}^0$ (T)	-21.40	-13.43

Note: In accord with the usual sign convention for heat transfer, negative values of  $E_{\text{fuel}}$  in above table show combustion reaction transfers heat to environment. It is converted to a positive value in the following study.

#### A.1.2.2 Energy associated with preheated combustion air

Another source of energy input to system is the combustion air, and preheated combustion air (after upgrades). The energy associated with combustion air  $E_{\text{comb air}} = 0$  as air taken directly from environment. The energy associated with preheated combustion air,  $E_{\text{preh air}}$ , is equal to the heat recovered in regenerator,  $Q_{\text{recovery}}$ . Refer to the following figure,

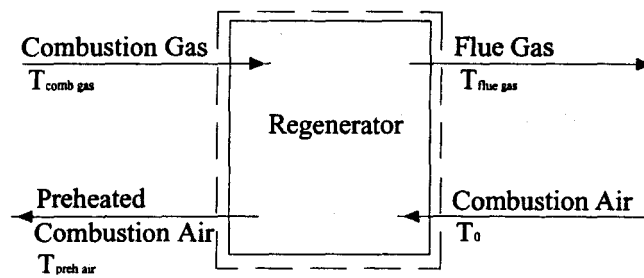


Figure A.1.2 Schematic of energy calculation of preheated combustion air

$$E_{\text{preh air}} = Q_{\text{recovery}} = n_{(\text{Fuel})} [n_{\text{O}_2} (\bar{h}_T - \bar{h}_0)_{\text{O}_2} + n_{\text{N}_2} (\bar{h}_T - \bar{h}_0)_{\text{N}_2}]$$

The values of enthalpy of the component are on basis of per kmole fuel. Recall energy balance equation 3.1 of furnace in section 3.1.3.1,

$$\text{Before upgrades, } E_{\text{input}} = E_{\text{fuel}} + E_{\text{solid metal}} + E_{\text{comb air}}$$

$$\text{After upgrades, } E_{\text{input}} = E_{\text{fuel}} + E_{\text{solid metal}} + (E_{\text{comb air}} + Q_{\text{recovery}})$$

With enthalpy values  $\bar{h}_T$  and  $\bar{h}_0$  from Tables A-17 and 18 in Moran and Shapiro, 1995, calculation results are tabulated in Table A.1.3,

Table A.1.3 Energy Input to Furnace Chamber

Items	Before upgrades	After upgrades
$T_{\text{comb air}} \text{ (K)}$	298	298
$T_{\text{preh air}} \text{ (K)}$		750
$E_{\text{comb air}} \text{ (TJ)}$	0	0
$E_{\text{preh air}} (=Q_{\text{recovery}}, \text{TJ})$		2.38
$E_{\text{source}} \text{ (TJ)}$	21.40	13.43
$E_{\text{solid metal}} \text{ (TJ)}$	0	0
$E_{\text{input}} = E_{\text{source}} + E_{\text{solid metal}} + (E_{\text{comb air}} + Q_{\text{recovery}}), \text{ (TJ)}$	21.40	15.81

Note:  $E_{\text{source}}$  values from Table A.1.2 are converted to positive when calculating total energy input.

The total energy input to furnace chamber also can be calculated via  $\bar{h}_p$  and  $\bar{h}_R$ , enthalpies of the combustion product and reactant per mole of fuel, the change of the two enthalpies presents the heat librated from combustion. The following figures are shown for before and after upgrades,

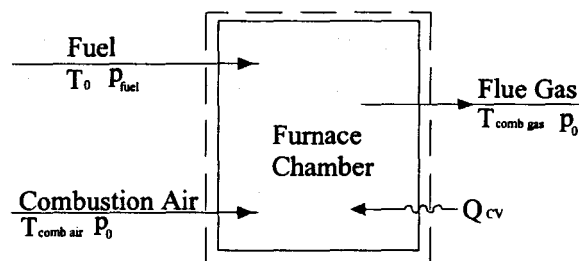


Figure A.1.2A Schematic of alternative energy input calculation before upgrade

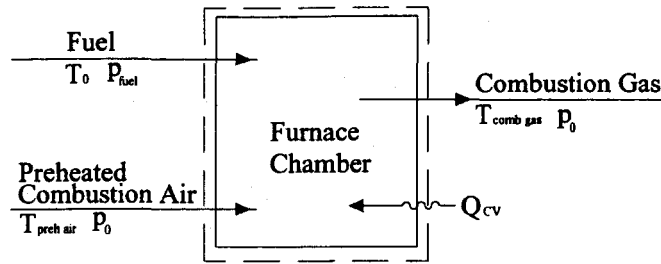


Figure A.1.2B Schematic of alternative energy input calculation after upgrade

Before upgrades,  $E_{\text{input}} = E_{\text{fuel}} + E_{\text{comb air}}$

Followed the combustion system's energy balance equations in section 13.2.2 in Moran and Shapiro, 1995,  $E_{\text{fuel}} + E_{\text{comb air}} = E_{\text{flue gas}} - Q_{\text{CV}}$

Similarly, after upgrades,  $E_{\text{input}} = E_{\text{fuel}} + E_{\text{preh air}} = E_{\text{comb gas}} - Q_{\text{CV}}$

Where  $Q_{\text{CV}} = n_{(\text{Fuel})} (\bar{h}_p - \bar{h}_R)$

$$\text{And } \bar{h}_p - \bar{h}_R \text{ (kJ/kmol fuel)} = \sum_P n_e (h_f^0 + [h(T_p) - h(T_0)])_e - \sum_R n_i (h_f^0 + [h(T_R) - h(T_0)])_i \quad (\text{A.5A})$$

$$\text{Then for before upgrades } E_{\text{fuel}} = E_{\text{input}} - E_{\text{comb air}} \quad (\text{A.5B})$$

$$\text{For after upgrades } E_{\text{fuel}} = E_{\text{input}} - E_{\text{preh air}} \quad (\text{A.5C})$$

Molar energy input of combustion based on per mole of fuel is found from  $E_{\text{input}} \times 10^9 / n_{(\text{Fuel})}$  (kJ/kmol fuel). All terms are defined as same as in previous section, all molar entropy values are based on per mole fuel and available in Tables A-17 to A-24 in Moran and Shapiro, 1995, and  $E_{\text{flue gas}}$  ( $E_{\text{comb gas}}$ ) need to be referred in next section A.1.3.2, the calculation results then are tabulated in the following table,

Table A.1.4 Alternative Calculation of Energy Input to Furnace Chamber

	Before upgrades	After upgrades
$\bar{h}_p$ (kJ/kmol fuel)	-500,176	-543,353
$\bar{h}_R$ (kJ/kmol fuel)	-76,700	82,148
$(\bar{h}_p - \bar{h}_R)$ (kJ/kmol fuel)	-423,476	-625,501
$n_{(Fuel)}$ (kmol)	23,890	14,993
$Q_{CV}$ (TJ)	-10.12	-9.38
$E_{flue\ gas} (E_{comb\ gas})$ (TJ)	11.28	6.43
$E_{input} = E_{flue\ gas} - Q_{CV}$ (TJ)	21.40	15.81
Molar energy input (kJ/kmol fuel)	895,761	1,054,609
$E_{comb\ air}$ (TJ)	0	0
$E_{preh\ air}$ (TJ)		2.38
$E_{fuel} = E_{input} - E_{comb\ air} (E_{preh\ air})$ (TJ)	21.40	13.43

The results  $E_{fuel}$  and  $E_{input}$  conform to the calculation results in Table A.1.3.

### A.1.3 Energy Output from Furnace System

Energy output from furnace chamber consists of three parts, energy associated with melted metal for production, with stack flue gas (or combustion gas) exiting furnace chamber, and with heat loss transferring to cooling water and furnace surroundings. These three parts of energy output are calculated separately as follows.

#### A.1.3.1 Energy change of metal in melting process

The total energy (heat) transferred to metal in the melting process is:

$$E_{melting} = Q_{melted\ metal} = Q_{m1} + Q_{fusion} + Q_{m2}$$

$$\text{Where heat transfer to solid metal, } Q_{m1} = c_1 m (T_{f1} - T_{i1}) \quad (A.6)$$

$$\text{Fusion heat to metal, } Q_{fusion} = n_{(metal)} \bar{c}_{f,alum} \quad (A.7)$$

$$\text{Heat transfer to liquid metal, } Q_{m2} = c_2 m (T_{f2} - T_{i2}) \quad (A.8)$$

$c_{p1}$ , specific heat for *solid* aluminium;  $c_{p2}$ , specific heat for *liquid* aluminium and  $\bar{c}_{f,alum}$ , specific heat of fusion for aluminium are taken from Kanicki and Kirgin, 1996.



$T_f$  and  $T_i$  denote final and initial temperatures, respectively, of melting metal. Heat transferred to melted aluminium ingot ( $m=1,972,000$  kg,  $n_{\text{(metal)}} = 73,145$  moles) are:

1) To heat metal from 298K ( $T_{i1}$ ) to 933K ( $T_{f1}$ ) (melting point), metal is solid,  $c_1 = 0.903$  kJ/kg.K; from equation (A.6),  $Q_{m1} = 1.13$  TJ

2) At melting point 933K, metal is mixture of solid and liquid,  $\bar{c}_{f, \text{alum}} = 10,790$  kJ/kmol, from equation (A.7),  $Q_f = 0.79$  TJ

3) To heat liquid metal from 933K ( $T_{i2}$ ) to 1033K ( $T_{f2}$ ), metal is liquid,  $c_2 = 1.17$  kJ/kg.K; from equation (A.8),  $Q_{m2} = 0.231$  TJ

Melting 1,972,000 kg ingot from 298K to 1033K, total consumed energy (heat transfer):

$$E_{\text{melting}} = Q_{m1} + Q_f + Q_{m2} = 1.13 + 0.79 + 0.231 = 2.15 \text{ TJ}$$

This is shown in Table 3.3. Based on explanation in section 3.1.1 (1), for reasonable comparison before and after upgrades, same quantity of solid metal material charge is considered. Thus, after upgrades, same amount of heat required for same quantity of production, i.e. 2.15 TJ. This is shown in Table 3.4.

#### A.1.3.2 Energy associated with flue gas

Energy associated with flue gas (and combustion gas after upgrades) can be calculated by sum of enthalpy of each component in the mixture of flue gas, refer to the following figures,

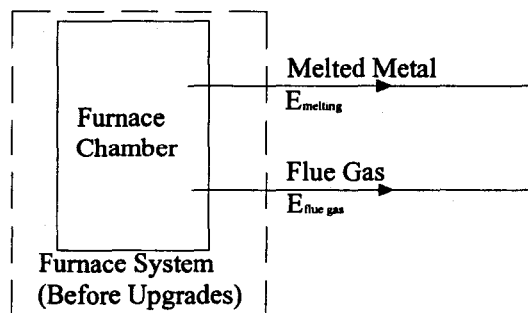


Figure A.1.3 Schematic of energy calculation of flue gas (before upgrades)

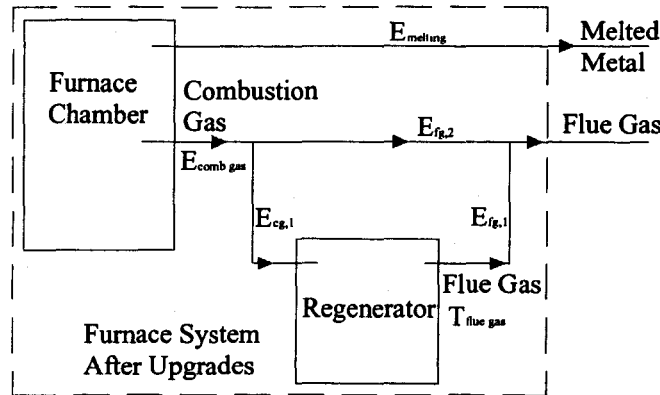


Figure A.1.4 Schematic of energy calculation of combustion gas and flue gas (after upgrades)

$$\begin{aligned}
 E_{\text{flue gas}} (E_{\text{comb gas}}) &= n_{(\text{Fuel})} \sum n_i (\bar{h}_T - \bar{h}_0)_i \\
 &= n_{(\text{Fuel})} [n_{\text{CO}_2} (\bar{h}_T - \bar{h}_0)_{\text{CO}_2} + n_{\text{O}_2} (\bar{h}_T - \bar{h}_0)_{\text{O}_2} + n_{\text{N}_2} (\bar{h}_T - \bar{h}_0)_{\text{N}_2} + n_{\text{H}_2\text{O}} (\bar{h}_T - \bar{h}_0)_{\text{H}_2\text{O}}] \quad (\text{A.9})
 \end{aligned}$$

The enthalpies of the component are on basis of per kmole fuel. After upgrades, the temperature of stack flue gas,  $T_{\text{flue gas}}$ , can be calculated by the enthalpy of the components of flue gas. Refer to the following figure,

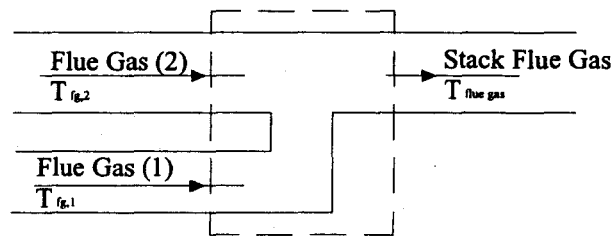


Figure A.1.4A Schematic of mixing flue gas

$E_{\text{flue gas}} = E_{\text{fg,1}} + E_{\text{fg,2}}$ . From the energy balance equation, it is found  $\Delta E_{\text{fg,1}} = \Delta E_{\text{fg,2}}$ . Being more specific, to a particular component in flue gas, , such as  $\text{CO}_2$ , then it's found  $(\Delta E_{\text{fg,1}})_{\text{CO}_2} = (\Delta E_{\text{fg,2}})_{\text{CO}_2}$

$$80\% n_{(\text{Fuel})} (\bar{h}_{\text{fg,1}} - \bar{h}_{\text{flue gas}})_{\text{CO}_2} = 20\% n_{(\text{Fuel})} (\bar{h}_{\text{flue gas}} - \bar{h}_{\text{fg,2}})_{\text{CO}_2}$$

$$(\bar{h}_{\text{flue gas}})_{\text{CO}_2} = (\bar{h}_{\text{fg},2} + 4\bar{h}_{\text{fg},1})/5$$

The enthalpies of the component are on basis of per kmole fuel. Extract temperatures and enthalpy values from previous, it is found  $(\bar{h}_{\text{flue gas}})_{\text{CO}_2} = 33,376 \text{ kJ/kmol fuel}$ . From Table A-21 in Moran and Shapiro, 1995,  $T_{\text{flue gas}} = 820 \text{ K}$  is found. The result can be validated by calculating enthalpy of other components in flue gas, such as,  $(\bar{h}_{\text{flue gas}})_{\text{O}_2} = 25,210 \text{ kJ/kmol fuel}$ ,  $(\bar{h}_{\text{flue gas}})_{\text{N}_2} = 24,381 \text{ kJ/kmol fuel}$ ,  $(\bar{h}_{\text{flue gas}})_{\text{H}_2\text{O}} = 28,853 \text{ kJ/kmol fuel}$ , and all the final temperatures conform to 820 K. The energy loss (heat rejection through flue gas duct to environment) is not considered since the loss can be merged to waste energy with mixed flue gas directly exiting to environment.

Summarizing data from above A.1.3.1 and A.1.3.2 for flue gas and combustion gas from furnace chamber, the following table is found:

Table A.1.5 Energy Calculation of Flue Gas and Combustion Gas

	Before upgrades	After upgrades		
$T_{\text{flue gas}} \text{ (K)}$	1180	$T_{\text{fg},1} = 700$	$T_{\text{fg},2} = 1280$	$T_{\text{flue gas}} = 820$
$\sum n_i(\bar{h}_T - \bar{h}_0)_i \text{ (kJ/kmol of fuel)}$	475,285	163,593	429,108	111,819
$E_{\text{flue gas}} \text{ (TJ)}$	11.28	$E_{\text{fg},1} = 1.29,$	$E_{\text{fg},2} = 1.96,$	$E_{\text{flue gas}} = 3.25$
$T_{\text{comb gas}} \text{ (K)}$		1280		
$E_{\text{comb gas}} \text{ (TJ)}$		6.43		
$E_{\text{cg},1} \text{ (TJ)}$		5.15		
$E_{\text{melting}} \text{ (TJ)}$	2.15	2.15		

### A.1.3.3 Energy loss from furnace chamber

As discussed in section 3.1.3.2, in furnace, the relationship between energy loss (heat loss) and energy balance can be shown as referring to the following figure,

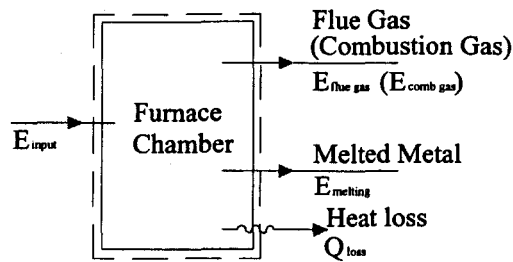


Figure A.1.5 Schematic of heat loss from furnace

$$Q_{\text{loss}} = E_{\text{input}} - E_{\text{transfer}} = E_{\text{input}} - E_{\text{melting}} - E_{\text{flue gas}}$$

The energy loss (heat loss) in regenerator is discussed in next subsection. Summarizing data from previous sections, energy loss in furnace can be found in following table:

Table A.1.6 Calculation of Energy Loss from Furnace Chamber

Items	Before upgrades	After upgrades
$E_{\text{input}}$ (TJ)	21.40	15.81
$E_{\text{melting}}$ (TJ)	2.15	2.15
$E_{\text{flue gas}} (E_{\text{comb gas}})$ (TJ)	11.28	6.43
$Q_{\text{loss}}$ (TJ)	7.97	7.23

#### A.1.3.4 Energy calculation in regenerator

As introduced in section 3.1.3.4, referring to the following figure, energy balance equation in regenerating process can be expressed as

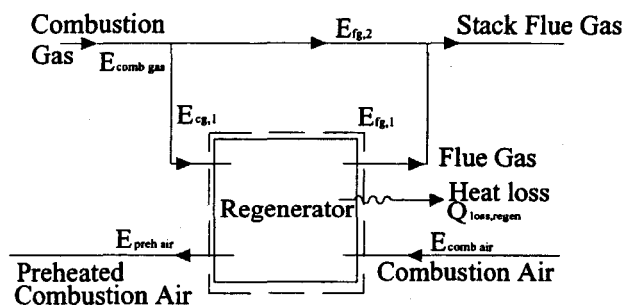


Figure 3.7 Schematic of energy balance in regenerator

$$E_{\text{input}} = E_{\text{output}}$$

Where  $E_{\text{input}} = E_{\text{cg},1} + E_{\text{comb air}}$

And  $E_{\text{output}} = E_{\text{preh air}} + E_{\text{fg},1} + Q_{\text{loss, regen}}$

$E_{\text{cg},1} = 0.80 E_{\text{comb gas}}$  while  $E_{\text{comb gas}}$  known in Table A.1.6, then  $Q_{\text{loss, regen}}$  can be calculated by all known terms from previous sections,

$$Q_{\text{loss, regen}} = (E_{\text{cg},1} + E_{\text{comb air}}) - (E_{\text{preh air}} + E_{\text{fg},1})$$

where  $E_{\text{comb air}} = 0$ , and the results are tabulated in the following table:

Table A.1.7 Energy Balance Calculation for Regenerator

Items	In Regenerator
$E_{\text{cg},1}$ (TJ)	$80\% \times 6.43 = 5.15$
$E_{\text{comb air}}$ (TJ)	0
$E_{\text{preh air}}$ (TJ)	2.38
$E_{\text{fg},1}$ (TJ)	1.96
$Q_{\text{loss, regen}}$ (TJ)	0.80

Note: The designed (minimum) 80% of combustion gas goes through regenerator and other (maximum) 20% of combustion gas bypass regenerator and exhaust from stack. The bypass design is for controlling and balancing internal pressure of regenerator. In real operation, bypass flue gas usually work at 10% of combustion gas. This helps to recover more heat and to increase overall efficiency.

The previous sections A.1.2 and A.1.3 list equations, formulas, calculation for energy analysis of the furnace before and after upgrades. The following detailed figure and table summarize and normalize the above results for reference.

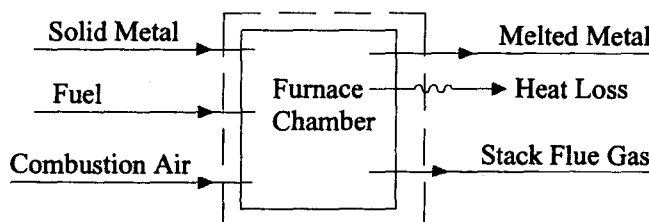


Figure A.1.6 Schematic of energy flows of furnace system before upgrades

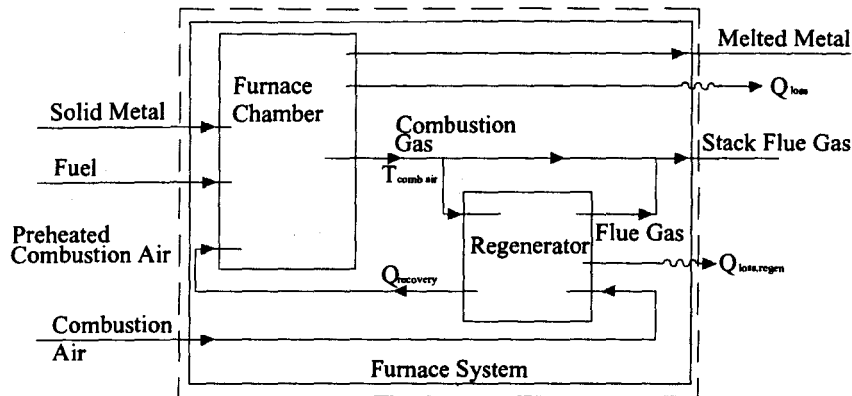


Figure A.1.7 Schematic of energy flows of furnace system after upgrades

Table A.1.8 Summary of Energy Flow Details for Before Upgrades and After

Energy Flows	Before Upgrades		After Upgrades	
	(TJ)	%	(TJ)	%
Fuel natural gas	21.40	100	13.43	100
Combustion air	0		0	
Solid metal	0		0	
Stack flue gas	11.28	53	3.25	24
Melted metal	2.15	10	2.15	16
Energy loss in furnace	7.97	37	7.23	54
Energy loss in regenerator			0.8	6
Preheated combustion air			2.38	15
Combustion gas			6.43	41
Combustion gas entering regenerator			5.15	33
Flue gas exiting regenerator			1.96	12

Note: 1% tolerance of normalized value sometimes caused by round off value.

The next section shows exergy calculation for the study.

#### A.1.4 Exergy Input to Furnace System

Exergy is calculated in this section through study of a combined system consisting of a furnace system and an environment. The object of the calculation is to express the maximum theoretical

work obtainable from the combined system as the furnace system comes into thermal and mechanical equilibrium with the environment.

Refer to the following figure and recall equations (A.3) and (A.4) as follows,

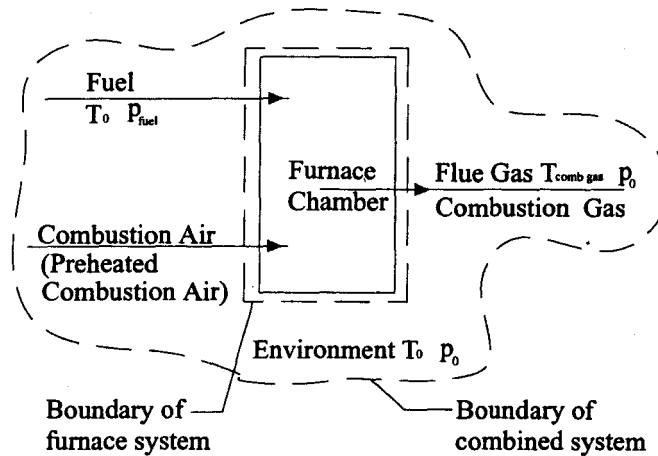


Figure A.1.8 Schematic of exergy calculation of fuel combustion



As addressed in Section 3.1.3.1, exergy input to furnace chamber is expressed by:

$$A_{\text{input}} = A_{\text{fuel}} + A_{\text{solid metal}} + (A_{\text{comb air}} + A_{\text{recovery}}) \quad (\text{A.10})$$

$A_{\text{comb air}} = 0$ , due to combustion air taken at temperature of reference environment

$A_{\text{solid metal}}$  are considered zero since the raw material are used at temperature of reference environment and no chemical reaction involved in melting process.

The following sections will discuss about  $A_{\text{input}}$ ,  $A_{\text{fuel}}$  and  $A_{\text{recovery}}$ .

#### A.1.4.1 Input exergy associated with combustion reaction

Exergy associated with fuel,  $A_{\text{Fuel}}$ , is the sum of two contributions, thermomechanical exergy ( $A_{\text{fuel}}^{\text{tm}}$ ) and chemical exergy ( $A_{\text{fuel}}^{\text{ch}}$ ), i.e.

$$A_{\text{Fuel}} = A_{\text{fuel}}^{\text{tm}} + A_{\text{fuel}}^{\text{ch}}$$

$$A_{\text{fuel}}^{\text{tm}} = n_{(\text{Fuel})} \bar{a}_{\text{fuel}}^{\text{tm}}$$

$\bar{a}_{\text{fuel}}^{\text{tm}}$ , molar thermomechanical exergy is obtained from following equation

$$\bar{a}_{\text{fuel}}^{\text{tm}} = (\bar{h} - \bar{h}_0) - T_0 (\bar{s} - \bar{s}_0) + \bar{R} T_0 \ln\left(\frac{P_{\text{fuel}}}{P_0}\right) \quad (\text{A.11})$$

$$A_{\text{fuel}}^{\text{ch}} = n_{(\text{Fuel})} \bar{a}_{\text{fuel}}^{\text{ch}}$$

$\bar{a}_{\text{fuel}}^{\text{ch}}$ , molar chemical exergy is obtained from following equation:

$$\bar{a}_{\text{fuel}}^{\text{ch}} = [\bar{g}_{f(\text{fuel})}^0 + n_{\text{O}_2} \bar{g}_{f(\text{O}_2)}^0] - [n_{\text{CO}_2} \bar{g}_{f(\text{CO}_2)}^0 + n_{\text{H}_2\text{O}} \bar{g}_{f(\text{H}_2\text{O})}^0 + \bar{R} T_0 \ln\left(\frac{(y_{\text{O}_2}^e)^{n_{\text{O}_2}}}{(y_{\text{CO}_2}^e)^{n_{\text{CO}_2}} (y_{\text{H}_2\text{O}}^e)^{n_{\text{H}_2\text{O}}}}\right)] \quad (\text{A.12})$$

$$\bar{g}_{f(\text{fuel})}^0 = -48,313 \text{ kJ/kmol}, \bar{g}_{f(\text{O}_2)}^0 = 0, \bar{g}_{f(\text{CO}_2)}^0 = -394,380 \text{ kJ/kmol}, \bar{g}_{f(\text{H}_2\text{O})}^0 = -228,590 \text{ kJ/kmol},$$

$y_i^e$  denotes molar fraction of  $i$  component of reactants and products in reference environment.

$y_i^e$  and  $n_i$  are listed in the following table:

Table A.1.9 Air Composition of Reference Environment and Combustion Gas

Component	$y_i^e$	$n_i$	
		Before Upgrades	After Upgrades
O <sub>2</sub>	0.21	3.14	2.45
CO <sub>2</sub>	0.0003	1.15	1.15
H <sub>2</sub> O <sub>(gas)</sub>	0.0303	2.15	2.15



$$\text{Before upgrades, } \bar{R}T_0 \ln\left(\frac{(0.21)^{3.14}}{(0.0003)^{1.15}(0.0303)^{2.15}}\right) = 23,035 \text{ kJ/kmol}$$

$$\text{After upgrades, } \bar{R}T_0 \ln\left(\frac{(0.21)^{2.45}}{(0.0003)^{1.15}(0.0303)^{2.15}}\right) = 32,258 \text{ kJ/kmol}$$

Some major terms in equation (A.11) and (A.12) are tabulated below:

Table A.1.10 Calculation of Fuel Exergy

Items	Before upgrades	After upgrades
$p_{\text{Fuel}} (10^5 \text{ Pa})$	1.15	1.70
$p_0 (10^5 \text{ Pa})$	1.01	1.01
$\bar{a}_{\text{fuel}}^{\text{im}} (\text{kJ/kmol})$	322	1,291
$A_{\text{fuel}}^{\text{im}} = n_{(\text{Fuel})} \bar{a}_{\text{fuel}}^{\text{im}} (\text{IJ})$	0.01	0.02
$T_0 = T_{\text{comb air}} (\text{K})$	298	298
$T_{\text{preh air}} (\text{K})$		750
$\bar{a}_{\text{fuel}}^{\text{ch}} (\text{kJ/kmol})$	919,728	928,951
$A_{\text{fuel}}^{\text{ch}} = \dot{n}_{\text{Fuel}} \bar{a}_{\text{fuel}}^{\text{ch}} (\text{IJ})$	21.97	13.93
$A_{\text{Fuel}} = A_{\text{fuel}}^{\text{im}} + A_{\text{fuel}}^{\text{ch}} (\text{IJ})$	21.98	13.95
Molar fuel exergy $\bar{a}_{\text{fuel}}^{\text{im}} + \bar{a}_{\text{fuel}}^{\text{ch}} (\text{kJ/kmol})$	920,050	930,242

#### A.1.4.2 Input exergy associated with combustion air

In equation (A.10) in last section, exergy input to furnace chamber includes exergy associated with combustion air. Before upgrades, no combustion air was preheated,  $A_{\text{comb air}} = 0$ , and  $A_{\text{recovery}} = 0$ .

After upgrades,  $A_{\text{comb air}} = 0$ , however, exergy associated with preheated combustion air is:

$$A_{\text{preh air}} (= A_{\text{recovery}}) = n_{(\text{Fuel})} \bar{a}_{\text{preh air}}$$

$\bar{a}_{\text{preh air}}$  denotes unit exergy of preheated combustion air on basis of per kmole of fuel,

$$\bar{a}_{\text{preh air}} = n_{\text{O}_2}[(\bar{h} - \bar{h}_0) - T_0(\bar{s} - \bar{s}_0)]_{(\text{O}_2)} + n_{\text{N}_2}[(\bar{h} - \bar{h}_0) - T_0(\bar{s} - \bar{s}_0)]_{(\text{N}_2)} \quad (\text{A.13})$$

The values of enthalpy of the component in equation (A.13) are on basis of per kmole fuel. Refer to Figure A.1.2 and Tables A-17 and A-18 in Moran and Shapiro, 1995, calculation results are tabulated in following table

Table A.1.11 Summary of Exergy Input

Items	Before upgrades	After upgrades
$T_{\text{comb air}} \text{ (K)}$	298	298
$T_{\text{preh air}} \text{ (K)}$		750
$A_{\text{comb air}} \text{ (TJ)}$	0	0
$A_{\text{preh air}} \text{ (TJ)}$		0.94
$A_{\text{recovery}} \text{ (TJ)}$		0.94
$A_{\text{solid metal}} \text{ (TJ)}$	0	0
$A_{\text{Fuel}} \text{ (TJ)}$	21.98	13.95
$A_{\text{input}} = A_{\text{fuel}} + A_{\text{solid metal}} + (A_{\text{air}} + A_{\text{recovery}}) \text{ (TJ)}$	21.98	14.89

## A.1.5 Exergy Output from Furnace System

Exergy outputs consist of three parts, which are exergy change of melted metal ( $\Delta A_{\text{metal}}$ ), exergy associated with flue gas ( $A_{\text{flue gas}}$ ) and with heat loss ( $A_{\text{loss}}$ ). These three parts of exergy output are calculated as follows.

### A.1.5.1 Exergy change of melted metal in melting process

Exergy change of melting metal from 298 K to 1033 K can be expressed as the sum of changes of thermomechanical and chemical contributions, i.e.

$$\Delta A_{\text{metal}} = \Delta A_{\text{metal}}^{\text{tm}} + \Delta A_{\text{metal}}^{\text{ch}}$$

$\Delta A_{\text{metal}}^{\text{tm}}$  denotes thermomechanical exergy change accompanying heat transfer to metal in melting process (not in fusion stage), it can be shown as follows. :

$$\Delta A_{\text{metal}}^{\text{tm}} = m [(h - h_0) - T_0 (s - s_0)]_{(\text{metal})}$$

where the values of enthalpy of the component are on basis of per kilogram metal. To breakdown the equation, the  $\Delta A_{metal}^{im}$  accompanying heat transfer to solid metal

$$\Delta A_{metal\ 1}^{im} = m [c_1 (T_{f,1} - T_{i,1}) - T_0 c_1 \ln(\frac{T_f}{T_i})]_{(1)} = Q_{m1} - T_0 m c_1 [\ln(\frac{T_f}{T_i})]_{(1)} \quad (A.14)$$

and the  $\Delta A_{metal}^{im}$  accompanying heat transfer to liquid metal,

$$\Delta A_{metal\ 2}^{im} = Q_{m2} - T_0 m c_2 [\ln(\frac{T_f}{T_i})]_{(2)} \quad (A.14.1)$$

and the  $\Delta A_{metal}^{im}$  accompanying fusion heat transfer to metal,

$$\Delta A_{metal\ f}^{im} = m [(h - h_0) - T_0 (s - s_0)]_{(metal\ fusion)} = Q_{fusion} - m T_0 (s - s_0)_{(metal\ fusion)} \quad (A.15)$$

The fusion heat transfer to metal can be treated as a internally reversible process, thus  $(s - s_0)_{(metal\ fusion)}$  denotes the entropy change in the internally reversible process on basis of unit mass, i.e.  $s - s_0 = Q_{fusion}/T_m$ . Recall  $Q_{fusion}$  from section A.1.3.1.  $T_m = 933\text{ K}$ , then equation (A.15) becomes

$$\Delta A_{metal\ f}^{im} = Q_{fusion}(1 - T_0/T_f) = 0.79 \times (1 - 298/933) = 0.54\text{ TJ}$$

The major terms in equation (A.14) and (A.14.1) are listed in the table below:

Table A.1.12 Part of Thermomechanical Exergy Change of Melted Metal

Items	298K ( $T_{i,1}$ ) to 933K ( $T_{f,1}$ )	933K ( $T_{i,2}$ ) to 1033K ( $T_{f,2}$ )
$Q_m$ (TJ)	1.13	0.23
$T_0 m$ (K x kg)	298 x 1,972,000	298 x 1,972,000
$c$ (kJ/kg.K)	0.903	1.17
$\ln(\frac{T_f}{T_i})$	$\ln(\frac{933}{298}) = 1.14$	$\ln(\frac{1033}{933}) = 0.1$
$\Delta A_{metal}^{im}$ (TJ)	0.53	0.15

$$\Delta A_{metal}^{im} = \Delta A_{metal\ 1}^{im} + \Delta A_{metal\ f}^{im} + \Delta A_{metal\ 2}^{im} = 0.53 + 0.54 + 0.15 = 1.22 \text{ TJ}$$

Standard chemical exergy of aluminium, from Szargut, 1988,  $\bar{a}_{metal}^{ch} = 888.4 \text{ kJ/kmol}$ , chemical exergy change of metal  $\Delta A_{metal}^{ch} = 0$  in the whole melting process.

Summarizing above, exergy change of melting metal is:

$$\Delta A_{metal} = \Delta A_{metal}^{im} + \Delta A_{metal}^{ch} = 1.22 + 0 = 1.22 \text{ TJ}$$

Since same production of melted metal is taken account for before and after upgrading, same exergy value is used for analysis after upgrades.

#### A.1.5.2 Output exergy associated with flue gas

Exergy of flue gas is sum of two contributions, thermomechanical exergy and chemical exergy, i.e.

$$A_{flue\ gas} = (A_{fluegas}^{im} + A_{fluegas}^{ch}) \quad (A.16)$$

$$\text{Where } A_{fluegas}^{im} = n_{(Fuel)} \bar{a}_{fluegas}^{im}$$

$\bar{a}_{fluegas}^{im}$ , denotes unit thermomechanical exergy on per mole of fuel basis, it can be expressed as:

$$\bar{a}_{fluegas}^{im} = \sum n_i [(\bar{h} - \bar{h}_0) - T_0(\bar{s} - \bar{s}_0)]_i \quad (A.17)$$

$$\text{And } A_{fluegas}^{ch} = n_{(Fuel)} \bar{a}_{fluegas}^{ch}$$

$\bar{a}_{fluegas}^{ch}$ , denotes unit chemical exergy on per mole of fuel basis, it can be expressed as:

$$\bar{a}_{fluegas}^{ch} = \bar{R}T_0 \sum_i n_i \ln\left(\frac{y_i}{y_i^e}\right) \quad (A.18)$$

where  $y_i$  and  $y_i^e$  denote the molar fraction of component  $i$  ( $\text{CO}_2$ ,  $\text{O}_2$ ,  $\text{N}_2$ , and  $\text{H}_2\text{O}$ ) in flue gas and in reference environment, respectively.  $y_i^e$ ,  $y_i$  and  $n_i$  are listed in the following table

Table A.1.13 Air Composition of Reference Environment and Combustion Gas

Component	$y_i^e$	Before Upgrades		After Upgrades	
		$y_i$	$n_i$	$y_i$	$n_i$
$\text{CO}_2$	0.0003	0.072	1.15	0.09	1.15
$\text{O}_2$	0.21	0.057	0.91	0.017	0.22
$\text{N}_2$	0.76	0.737	11.8	0.723	9.21
$\text{H}_2\text{O}_{(\text{gas})}$	0.0303	0.134	2.15	0.169	2.15

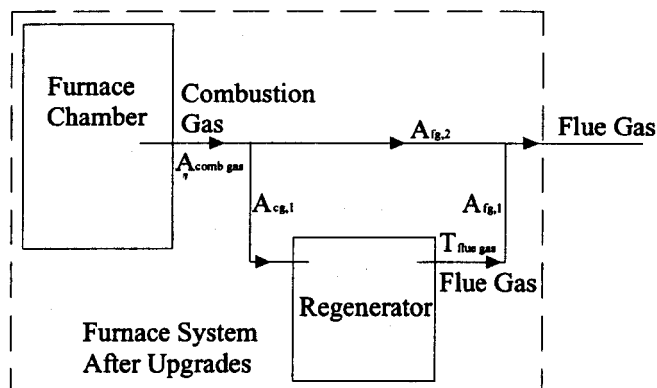


Figure A.1.9 Schematic of exergy of flue gas and combustion gas

Refer to the above figure, some major calculated results in equations A.16, A.17 and A.18 are listed in the following table:

Table A.1.14 Exergy Calculation for Stack Flue Gas and Combustion Gas

Items	Before upgrades	After upgrades
<b>Stack Flue Gas</b>		
$T_{\text{flue gas}}$ (K)	1180	820
$\bar{a}_{\text{flue gas}}^{\text{im}}$ (kJ/kmol fuel)	257,661	92,408
$\bar{a}_{\text{flue gas}}^{\text{ch}}$ (kJ/kmol fuel)	19,704	22,865
$A_{\text{flue gas}} = n_{(\text{Fuel})} (\bar{a}_{\text{flue gas}}^{\text{im}} + \bar{a}_{\text{flue gas}}^{\text{ch}}) (T)$	6.63	1.73
<b>Internal flows</b>		
$\bar{a}_{\text{cg}}^{\text{im}}$ (kJ/kmol fuel)		244,422
$\bar{a}_{\text{cg}}^{\text{ch}}$ (kJ/kmol fuel)		22,865
$A_{\text{comb gas}} = n_{(\text{Fuel})} (\bar{a}_{\text{cg}}^{\text{im}} + \bar{a}_{\text{cg}}^{\text{ch}}) (T)$		4.01
$A_{\text{cg},1}$ (TJ)		3.21
$A_{\text{fg},1}$ (TJ)		1.0
$A_{\text{fg},2}$ (TJ)		0.8

All specific enthalpy and entropy values of each component in flue gas can be found in Tables A-14 to A-24 in Moran and Shapiro, 1995.

### A.1.5.3 Exergy loss and exergy destruction

#### 1) Exergy loss and destruction in furnace chamber

As equation 3.6 discussed in section 3.1.3.1, in furnace chamber where combustion takes place, refer to the following figure, the exergy loss accompanying heat loss can be expressed as following,

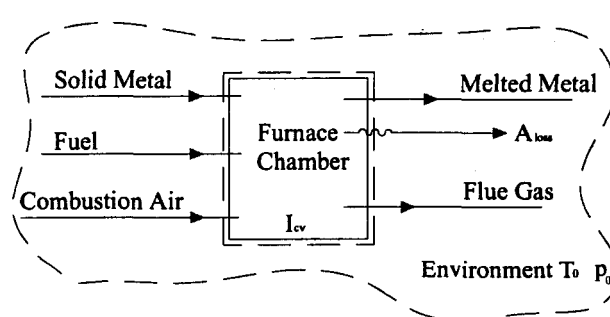


Figure 3.5 Schematic of exergy loss from furnace chamber to environment

$$A_{\text{loss}} = Q_{\text{loss}} (1 - T_0 / T_{\text{loss}}) \quad (\text{A.19})$$

As discussed in section 3.1.3.1,  $T_{\text{loss}} = 420\text{K}$  is taken in this study. Then, taking data from Table A.1.6, the exergy loss accompanying heat loss from furnace chamber is found

Before upgrades,  $A_{\text{loss},1} = 7.97 (1 - 298/420) = 2.31 \text{ TJ}$

After upgrades,  $A_{\text{loss},2} = 7.23 (1 - 298/420) = 2.10 \text{ TJ}$

The minor change of energy loss (7.97 TJ vs. 7.23 TJ) supports that the hypothetical mean temperature,  $T_{\text{loss}}$ , is not changed obviously after upgrades. Exergy destruction can be found from exergy balance equation:

$$I_{\text{CV}} = A_{\text{input}} - A_{\text{transfer}} - A_{\text{loss}}$$

Being more specific, in furnace chamber, exergy destruction is:

Before upgrades,  $I_{\text{CV},1} = A_{\text{input}} - (\Delta A_{\text{metal}} + A_{\text{flue gas}}) - A_{\text{loss}} = 21.98 - (1.22 + 6.63) - 2.31 = 13.87 \text{ TJ}$

After upgrades,  $I_{\text{CV},2} = A_{\text{input}} - (\Delta A_{\text{metal}} + A_{\text{comb gas}}) - A_{\text{loss}} = 16.64 - (1.22 + 4.01) - 2.10 = 12.10 \text{ TJ}$

## 2) Exergy loss and destruction in regenerator

Refer to the following figure for exergy flows in regenerator, ,

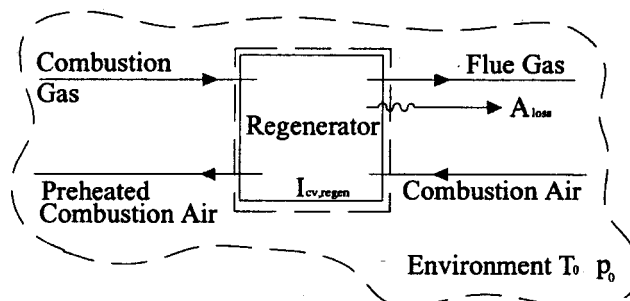


Figure A.1.10 Schematic of exergy loss from regenerator to environment

Exergy loss accompanying heat transfer to environment can be expressed as

$$A_{\text{loss,regen}} = Q_{\text{loss,regen}} (1 - T_0 / T_{\text{loss,regen}})$$

Where  $T_{\text{loss,regen}} = 325 \text{ K}$  ( $52^\circ \text{C}$ ) is taken for regenerator. Then exergy loss in regenerator is found

$$A_{\text{loss,regen}} = 0.80 (1 - 298/325) = 0.07 \text{ TJ}$$

From exergy balance equation in regenerator and Figure A.1.8., exergy destruction can be expressed as

$$I_{\text{CV,regen}} = A_{\text{input}} - A_{\text{transfer}} - A_{\text{loss}} = (A_{\text{comb air}} + A_{\text{cg,1}}) - (A_{\text{preh air}} + A_{\text{fg,1}}) - A_{\text{loss}} = (0 + 3.21) - (0.94 + 1.0) - 0.07 = 1.2 \text{ TJ}$$

### 3) Exergy loss and destruction in mixing flue gas

Like many heat exchange process, mixing flue gas from regenerator and bypass flue gas result in exergy destruction. Exergy loss accompanying heat loss through flue duct to environment is not considered since the flue gas exits to environment directly. Refer to the following figure, the exergy flows and destruction are found,

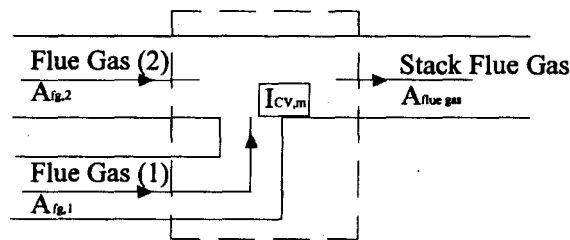


Figure A.1.11 Schematic of exergy flows of mixing flue gas

$$I_{\text{CV,mix}} = A_{\text{fg,1}} + A_{\text{fg,2}} - A_{\text{fg}}$$

All terms at right side of equation are known from previous sections,  $I_{\text{CV,mix}} = 1.0 + 0.8 - 1.73 = 0.07 \text{ TJ}$



Refer to following integrated figure, all above calculations are summarized, listed and normalized below for reference.

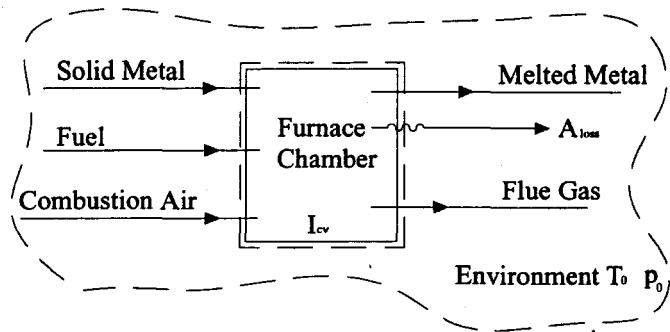


Figure 3.5 Schematic of exergy flows of furnace system before upgrades

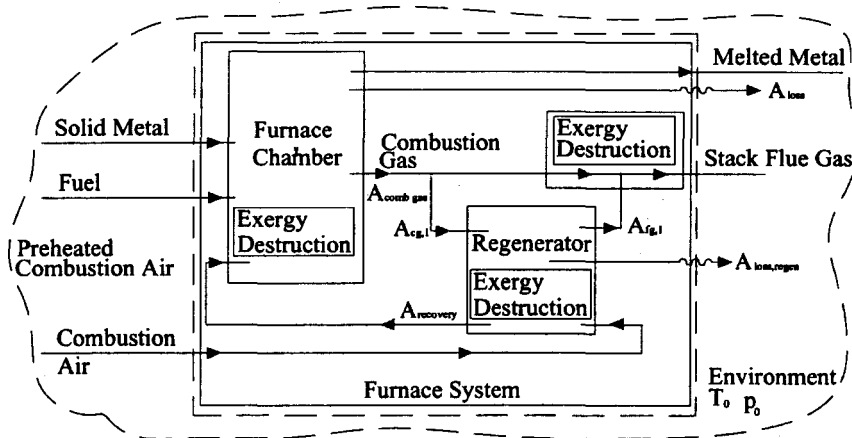


Figure A.1.12 Schematic of exergy flows of furnace system after upgrades

Table A.1.15 Summary of Exergy Flow Details for Before Upgrades and After

Items	Before Upgrades		After Upgrades	
	(TJ)	%	(TJ)	%
Fuel natural gas	21.98	100	13.95	100
Thermomechanical exergy contribution	0.01	0.05	0.02	0.01
Chemical exergy contribution	21.97	99.95	13.93	99.99
Combustion air	0		0	
Solid metal	0		0	
Stack flue gas	6.63	30	1.73	12
Melted metal	1.22	6	1.22	9
Exergy loss from furnace	2.31	11	2.10	15
Exergy loss from regenerator			0.07	0.5
Exergy destruction in furnace	11.82	53	7.56	54
Exergy destruction in regenerator			1.2	9
Exergy destruction in flue gas mixing			0.07	0.5
Preheated combustion air			0.94	6
Combustion gas			4.01	27
Combustion gas entering regenerator			3.21	22
Flue gas exiting regenerator			1.0	7