Exergy-based Analysis and Efficiency Evaluation for an Aluminum Melting Furnace in a Die-casting Plant

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Abstract: The efficiency of a natural gas-fired aluminum melting furnace in a die-casting plant is examined using energy and exergy methods, to improve understanding of the burner system in the furnace and so that potential improvements can be identified. Such improvements not only reduce fuel consumption, but also mitigate environmental emissions and impacts such as climate change. The insights gained through the assessments into the melting furnace are described and potential improvements indicated are discussed. The results confirm that exergy analysis can be used beneficially to analyze and improve the furnace efficiency and that exergy efficiency is a more practical measure in reality. It is anticipated that the results will be of interest and benefit to designers of new and retrofit systems.

Keywords: Exergy, Efficiency, Energy, Aluminum, Melting Furnace, Die-casting

1 Introduction

Environmental objectives imply that fossil fuel consumption and emissions must be reduced. Natural gas is a commonly used fossil fuel used in industrial, commercial and domestic applications. Efforts to control natural gas emissions are being made, even though its emissions per unit fuel energy are lower than those for oil and coal.

Die casting is used in many industries, including automotive. In recent years, the material used in die casting has shifted from iron and steel to aluminum, leading to an increase in the use of aluminum casting.

In this paper, which builds on an earlier investigation [1], the efficiency of a natural gas-fired aluminum melting furnace in a die-casting plant is examined using energy and exergy methods, to improve understanding of the burner system in the furnace and to identify potential improvements. The Dym Eto Casting (DEC) plant is selected as a representative plant. In the paper, die casting and the efficiency of the melting furnace are described, energy and exergy assessments are reported of the natural gas-fired aluminum melting furnace in a die-casting plant, and the results are discussed, including ways in which improvements can mitigate environmental emissions and impacts such as climate change.

2 Metal Die Casting

The metal casting industry uses molten metal to form cast metal components for manufactured products. The largest uses of cast metal products include vehicles, railroads and construction equipment.

2.1 Process

The basic casting process involves four main steps:

- Pattern making: Using metal to construct a model of the designed cast part and a mold through which molten metal can be poured into the model.
- Metal melting: Melting ingot and scraps in a furnace, using electricity or fuel. This step consumes much energy. The furnace in the DEC plant considered here uses natural gas.
- Die casting: Pouring molten metal into the mold, cooling and removing the mold. This step is energy intensive. Usually cooling water is used

to cool the model, and warmed cooling water can be utilized for space or other heating. In summer, however, cooling water rejects heat to the atmosphere through a cooling tower.

- Finishing: Cleaning and coating the casting, and recycling scrap.

This study focuses on the melting furnace, which has 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.

2.2 Aluminum casting

There are two main types of metal used in die casting: ferrous and nonferrous. High-volume production in the nonferrous sector is accomplished with die-casting. Aluminum casting has experienced continuous growth [2]. Aluminum castings also dominate the nonferrous sector in general, comprising 78% of total nonferrous shipments.

One kilogram of cast aluminum alloy can offset the weight of 5.0 to 5.5 kilogram of cast iron. Since aluminum is three to five times as expensive as steel on a mass basis, the effective cost of aluminum in automotive applications is roughly 133 to 200 percent the cost of steel. Growing demands for lightweight vehicles have increased aluminum die casting.

3 Exergy Analysis

Exergy is defined as the maximum work which can be produced by a system or stream of matter or energy as it comes to equilibrium with a reference environment [3]. Exergy analysis is a method for assessing systems and processes [4, 5]. Exergy analysis differs from energy analysis and is more practical. Energy analysis is based on the first law of thermodynamics while exergy is based on the first and second laws. The second law addresses energy quality and asserts that exergy is destroyed during an irreversible process [6]. Other second-law-based methods exist [7-10], but exergy is one of the most common. Unlike energy, exergy is not conserved and the initial exergy is destroyed at least in part by process irreversibilities.

4 Process Investigated

The DEC aluminum die casting plant, established in 1965 in Toronto, Ontario, Canada, supplies cast parts including engine pistons for automotive vehicles. At the time of this study, the plant operates 24 hours a day, 7 days a week, about 50 weeks a year. There are four melting/holding furnaces under manual operation for die casting production and three automatic production lines for piston casting. Three melting furnaces were constructed when the plant was built, and another one was added in the early 1990s. Three automotive piston lines were set up in the mid 1990s.

Figure 1 illustrates the furnace, which discharges melted aluminum. The outer boundary represents the furnace system, which contains the combustion chamber and the stack. This study focuses on Furnace #3, a direct natural gas-fired furnace which has the largest capacity among the four manual operating furnaces. During operation, 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 burners are mounted at the end wall without material charge and discharge. Stack gas leaves the furnace at the opposite side to the burners.

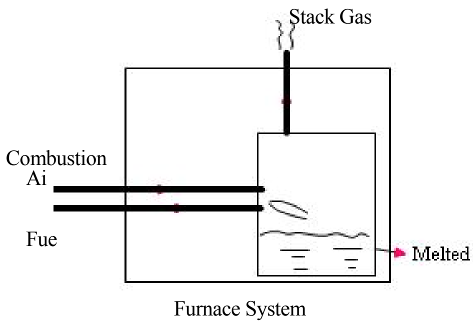

Fig. 1. Illustration of furnace operation.

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

5 Analysis of Furnace

The process is illustrated in Fig. 2. The rectangle represents the furnace system, including the combustion chamber. The dashed line denotes boundary of the combined system including the furnace system and the reference environment, which is assumed to be at 25°C and 1 atm (1.01×10^5 Pa).

5.1 Process data

Data on material and energy consumption were collected from production logs and information on the process was obtained from operation control system, facilities administration personnel and archived plant documents. Table 1 lists furnace process data, including fuel consumption, combustion air input, melted metal production and stack gas exhausted.

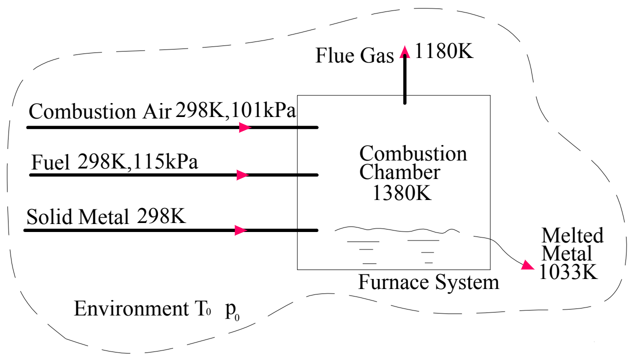

Fig. 2. Furnace system and its reference environment.

Table 1. Process data for melting furnace

Item	Quantity		Temp.	Pres.
	Vol. (m^3)	Mass (kg)	(K)	(MPa)
Natural gas	514,692	383,198	298	0.115
Combustion air	1,837,422	2,163,435	298	0.101
Solid metal		1,972,000	298	0.101
Stack gas	8,809,656	2,546,633	1180	0.101
Melted metal		1,972,000	1033	0.101

5.2 Fuel consumption and production days

To permit a reasonable comparison, energy and exergy analyses are carried out for 1,972,000 kg production. The production schedule at the time of this study was 3 shifts per day, 6 days per week. From December 2002 to March 2003, there were total 96 working days, but 44 working days were not operating at full production capacity due to maintenance and holiday shutdowns. During the remaining 52 working days, a total of 1,972,000 kg ingot and scraps were charged in batches. Melted metal loss occurs in melting and conveying, but is neglected since the amount of liquid aluminum loss is very small (less than 0.01 % from plant experience). Fuel consumption data are taken from the daily log of natural gas meter readings. Previous material and fuel consumption is based on the latest recorded statistics (1993); these are considered valid since the furnace performed consistently according to material and fuel logs during then and the time of this investigation. Product operation personnel in the plant reported that 1 kg ingot input requires on average 0.261 m^3 fuel. Therefore 514,692 m^3 gas is used to produce 1,972,000 kg melted metal. The natural gas supply gauge pressure is 115 kPa (2 psi), and its higher heating value is approximately 55.8 MJ/kg.

5.3 Raw material analysis

Calculations are based for simplicity on a pure aluminum ingot, even though the actual material used in melting and casting is alloy 306, whose properties are different from pure aluminum. The melting process of alloy 306 is more complicated than that of pure aluminum. Normally the specific heat of an aluminum alloy is lower than that of pure aluminum, meaning the alloy needs less heat than the same mass of aluminum to reach the same temperature. Plant records indicate that alloy 306 consists of 84% aluminum, 10% Si, 3.5% Cu, 1% Fe and 1.5% other substances. Modelling alloy 306 as aluminum is reasonable since its main constituent is aluminum. Note that scraps are recycled from processes in the plant and the scrap quality is considered to be the same as the ingot. References to “material” or “ingots” in this study include scraps.

5.4 Combustion air, stack and combustion gas

Combustion air is supplied by a fan drawing indoor air from the plant. To balance the plant indoor air pressure, plant pressurization is controlled by a group of air handling units. The quantity of combustion air and the quantity of stack gas are computed from the quantity of fuel consumed, i.e. based on chemical equations in [1]. In 1993, the temperature of the combustion products for the plant was recorded as 1360 K; previous testing recorded the stack gas temperature as 1180 K.

5.5 Hot charge

To maintain the furnace temperature after the melted metal is discharged for casting, a hot charge of melted liquid aluminum is delivered to furnace in batches at 1033-1088 K. Hot charges are held in the furnace for a short time (several hours) during a normal production day. After new batches of ingot enter the furnace and are melted, a mixture of hot charge and newly melted metal is delivered for casting at 1033 K. The hot charge remains in the system for a short time and consumes almost no energy, therefore the hot charge is neglected in calculations.

6 Thermodynamic Analysis of Furnace

Energy and exergy balances and efficiencies are obtained for the furnace system, following the approach in [11]. The reference-environment temperature T_0 and pressure p_0 are taken to be 25°C and 1 atm, respectively.

6.1 Assumptions

The following assumptions are made: 1) the system assessed (Fig. 1) operates at steady state, and has no work interactions; 2) the fuel and combustion products behave as ideal gas mixtures; 3) combustion products exit the furnace through the stack; 4) electricity consumption for motors, monitoring and control devices is neglected because it is small compared to the fuel energy; and 5) although the fuel supplied by the natural gas vender includes nitrogen (N_2), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and water vapor (H_2O) [12], the volumes of N_2, CO_2, H_2S and H_2O are neglected because they are small.

6.2 Fuel combustion

Excluding minor constituents, the molar composition of natural gas is 90.00% methane (CH_4), 4.63% ethane (C_2H_6), 3.91% propane (C_3H_8), 0.98% butane (C_4H_{10}) and 0.08% pentane (C_5H_{12}) [13]. The combustion in air of 1 mole of natural gas can be written as

$$(0.9\ CH_4 + 0.0463\ C_2H_6 + 0.0391\ C_3H_8 + 0.0098\ C_4H_{10} + 0.0008\ C_5H_{12}) + n(O_2 + 3.76\ N_2) \rightarrow 1.15\ CO_2 + (n - 2.23)\ O_2 + (3.76n)\ N_2 + 2.15\ H_2O$$

The coefficient n in the above equation is determined to be 3.14 using the results of stack testing (on wet basis) on the furnace, which determined that the combustion products contain 6% O_2 by volume. The actual air-fuel ratio on a molar basis is $A/F = (3.14/1) \times 4.76 = 14.95$, and is controlled by furnace operators via observations of the flame color.

6.3 Balances and efficiencies for furnace

The energy input and output of furnace can be expressed following Fig. 3 as

$$E_{input} = E_{source} + E_{solid\ metal} + E_{comb\ air}$$

$$E_{output} = E_{melted\ metal} + E_{stack\ gas} + Q_{loss} + Q_{loss,\ regen} = (E_{solid\ metal} + \Delta E_{metal}) + E_{stack\ gas} + Q_{loss}$$

where $E_{comb\ air} = E_{solid\ metal} = 0$. An energy balance can be expressed as

$$E_{input} = E_{output}$$

Here, $E_{product}$ is the heat transferred to melted metal, E_{input} is the energy generated from fuel combustion, and E_{loss} includes all energy losses for the system.

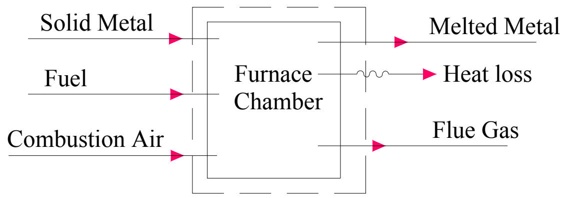

Fig. 3. Energy flows through the furnace system.

The exergy input and output for the furnace chamber can be written following Fig. 4 as follows:

$$A_{input} = A_{fuel} + A_{solid\ metal} + A_{comb\ air}$$

$$A_{output} = A_{melted\ metal} + A_{stack\ gas} + A_{loss} = (A_{solid\ metal} + \Delta A_{metal}) + A_{stack\ gas} + A_{loss}$$

where $A_{comb\ air} = 0$. An exergy balance is

$$A_{input} = A_{output} + I_{CV}$$

Here, $A_{product}$ is the exergy transferred to melted metal, A_{input} is the exergy generated from fuel combustion, and A_{loss} is the exergy associated with system energy losses. Exergy is not conserved, so $A_{input} > A_{output}$.

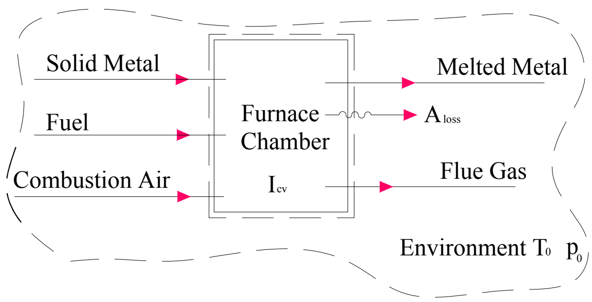

Fig. 4. Exergy flows through the furnace system in a reference environment.

(3)

The energy (exergy) loss in the furnace chamber, Q_{loss} (A_{loss}), is associated with combustion, melting and (4) water cooling. The energy (exergy) loss exits in various ways, including thermal radiation and convection through furnace walls and heat leakage from furnace doors. The energy (exergy) associated with cooling water is also part of the loss. The energy loss in furnace chamber can be determined with the energy balance in equation (3) as follows:

$$Q_{loss} = E_{input} - \Delta E_{metal} - E_{stack\ gas}$$

The corresponding exergy loss in furnace chamber is evaluated with equation (4) as

$$A_{loss} = Q_{loss}(1 - T_0/T_{loss})$$

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Here, T_{loss} denotes a hypothetical mean temperature of the general heat loss from the furnace chamber to the environment. The overall heat loss includes losses from the furnace body, leakage through the door and heat transfer to the cooling water. The mean temperature is a datum for estimating the exergy loss accompanying the overall heat loss, and is taken to be T_{loss} = 420 K in this study. For typical furnace operation, it is observed that the furnace heat loss varies only slightly.

With equations (5), (6) and (7), the exergy destruction in the furnace chamber is found to be

$$I_{CV} = A_{input} - A_{transfer} - A_{loss} = A_{input} - (\Delta A_{metal} + A_{stack\ gas}) - A_{loss} \quad (10)$$

Here, I_{CV} includes exergy destructions associated with combustion, melting, water cooling and other phenomena inside the furnace chamber.

Alternatively, the exergy loss and destruction for the furnace chamber can be considered in combination when convenient or desirable [14]. Then, with equations (2) and (3),

$$A_{loss} + I_{CV} = A_{input} - A_{transfer} = A_{input} - (\Delta A_{metal} + A_{stack\ gas})$$

The energy efficiency η of the melting furnace is the ratio of product energy to energy input, while the exergy efficiency ε is the ratio of product exergy to exergy input. Hence,

$$\eta = \Delta E_{metal}/E_{fuel} \quad (11)$$

$$\varepsilon = \Delta A_{metal}/A_{fuel} \quad (12)$$

7 Results and Discussion

7.1 Furnace energy and exergy balances

Tables 2 and 3 present energy and exergy balances respectively of the furnace system, for the operating period considered (52 working days).

7.2 Furnace energy and exergy efficiencies

In Tables 2 and 3, the energy and exergy efficiencies of the overall furnace are observed to be 10% (2.15/21.40 × 100%) and 6% (1.22/21.98 × 100%), respectively. In real operation, the furnace melting efficiency may be below 10%, in part because electricity is neglected in the overall energy input. Other factors may increase energy efficiency, like shorter holding times and greater charged ingots.

Table 2. Furnace energy balance

Quantity	Energy flow TJ/period	Energy flow % of input
Energy input		
Fuel (natural gas)	21.40	100
Combustion air	0.00	0
Solid metal	0.00	0
Total	21.40	100
Energy output		
Stack gas	11.28	53
Melted metal	2.15	10
Furnace loss	9.97	37
Total	21.40	100

Table 3. Furnace exergy balance

Quantity	Exergy flow TJ/period	Exergy flow % of input
Exergy input		
Fuel exergy	21.98	100
Thermomechanical	0.01	0
Chemical	21.97	100
Combustion air	0.00	0
Solid metal	0.00	0
Total	21.98	100
Exergy output		
Stack gas	6.63	30
Melted metal	1.22	6
Furnace loss	2.31	11
Total	10.16	47
Exergy destruction	11.82	53

The total lost energy is 90% of the input energy. Heat rejection to the environment from stack gas is significant, accounting for over half the energy output. Energy loss from furnace chamber is also important, at almost 40% of the energy input.

The exergy supplied to the process, 21.98 TJ, is almost the same as the energy supplied, due to the fact that the chemical energy and exergy of fossil fuels are almost equal. The molar fuel thermomechanical exergy is 322 kJ/kmol, and the thermomechanical contribution to the natural gas exergy is small (0.05%) compared to the chemical contribution. The molar chemical exergy of the fuel is 919,728 kJ/kmol and the overall chemical exergy input is 21.97 TJ.

The exergy loss includes waste emissions and internal destructions. The exergy in the stack gas is 6.63 TJ, while the exergy loss and destruction from the furnace chamber is 14.13 TJ (2.31 TJ furnace exergy loss plus 11.82 TJ exergy destruction). Processes within the furnace chamber destroy 53% of exergy input and represent the largest exergy loss in the system; this loss is associated with irreversibilities in the processes of combustion, heat transfer and melting. The overall exergy loss of 20.76 TJ 6.63 + 2.31 + 11.82) indicates the margin available for furnace performance improvement.

8 Conclusions

This investigation of aluminum melting using energy and exergy methods has revealed numerous insights. The overall-system energy efficiency is 10% and exergy efficiency is 6%. Irreversibilities due to natural gas combustion, melting and water cooling within the furnace chamber destroy more than 50% of exergy input, representing the largest exergy loss in the system. The thermomechanical exergy of the fuel is very small compared to the chemical exergy. The results confirm that exergy analysis is a more practical and useful tool than the more conventional energy analysis for assessing and comparing the performance of the melting furnace. Consequently, efforts to improve the efficiency of the process appear to be worthwhile. Possible measures being investigated by the authors include adding regenerative burners and regenerators, preheating ingots, using compressed natural gas, reclaiming heat from cooling water, and replacing combustion air.

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