Lessons Learned from Industrial Assessments of Metal Casting Facilities

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ABSTRACT

This paper presents recommendations for saving energy that are based on ten industrial energy assessments performed at metal casting facilities and foundries. The facilities assessed produce castings of aluminum, copper, bronze, iron and steel. They utilize a variety of molding processes and require large amounts of energy. The energy sources used for melting were electricity, natural gas, and coke, while support activities involved the use of natural gas and electricity.

Recommendations that are of interest to all foundries and metal casting companies are discussed. In particular, analysis is presented for improvements in:

- Process melting energy
- Operating combustion blowers and exhaust fans
- Opportunities for combining heat and power

Process melting energy accounts for the majority of energy costs in all foundries, and can be significantly reduced by decreasing heat losses. The major heat losses observed were due to: i) high temperature exhaust gases, ii) cooling water losses for electric induction coils, and iii) lack of proper furnace insulation. Methods of reducing each of these losses are discussed.

The energy usage by air exhaust fans and combustion air blowers offers additional opportunities for savings. The extent of improvement in these systems through the use of two-speed or variable speed drives is discussed.

Finally, the simultaneous need for heat and electricity at most of these sites provides an opportunity for combined heat and power (CHP) systems. The potential applicability of a CHP system is explored to meet the needs of these metal casting facilities and foundries.

Introduction

The typical metal casting firm assessed has fewer than 500 employees and annual energy costs of less than $1.5 million. These companies represent the backbone of metal casting throughout much of the state of Michigan and the country (Energetics 1999). Reports of similar assessment include those made at an iron foundry (Meffert 1999) and an analysis of replacing a cupola with an electrical furnace at an iron foundry (Wick et al. 1998)

The numbers discussed in the report result from assessments to a variety of metal casting companies that melt alloys of aluminum, brass, copper, iron and steel. These companies use different technologies for melting, such as reverbatory, crucible, blast, electrical resistance and induction furnaces, which are powered by electricity, natural gas and coke. A general overview of the industry is presented and specific recommendations that could be useful to a variety of manufacturers are presented. These recommendations are detailed in Table 1.

Table 1. Recommendations and their Application to the Metal Casting Industry

Recommendations	Application	Example	Size of equipment	Savings
Exhaust Heat Recovery	Foundry/Heat treat /w hydrocarbon fuel	Heat Treat/w Natural Gas	6 million Btu/hr	14%
Cooling water heat recovery	Electrical furnaces during winter	Electrical Furnaces	500 kW	20% in winter
Cover Furnaces	All high temperature surfaces and openings	Metal Casting	3 feet diameter Holding Furnace	70%
Variable Speed Drives	Dust collection and combustion air	Combustion Blower	300 hp	29%
Combined Heat and Power	Facilities with on-site power generation	Gas Turbine	3 MW	14% +

The recommendations identify opportunities in process heating and support activities. Specific examples are described in the text; however, individual savings will vary with equipment size, utilization, casting material and process. For example, the exhaust temperature of the gas can determine the fraction of energy recovered from a natural gas-powered casting furnace. The cost savings will depend on the size of the furnace and the time it is on high fire, which varies from facility to facility. Likewise, reusing cooling water from electrical furnaces for heating will depend on plant location and time of the year.

Operations and End Use of Energy at Metal Casting Facilities

Operations and End User Energy (EUE) required by a metal casting foundry are shown in the Figure 1.[1] Typical production steps are: pattern design and construction, core making and mold forming, melting, pouring, shake out, cut off and finishing. Pattern design and construction are crucial to the production steps. However they consume much less energy than any of the other steps, requiring

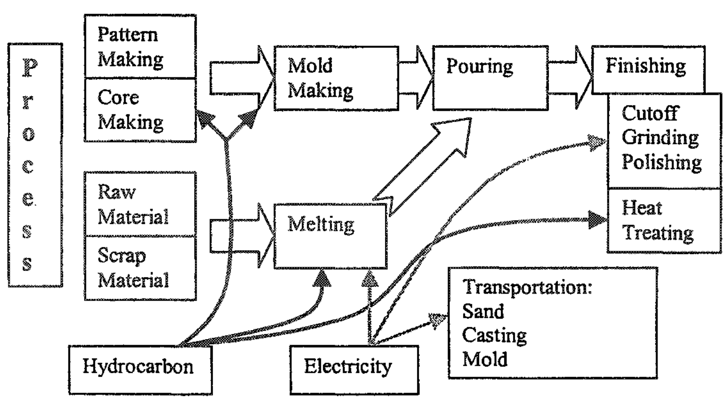

Figure 1. Process and End Energy Use for a Typical Metal Casting Company

1 End user energy is the form of energy that is used by the industrial company. This could take the form of natural gas, coal, coke, petroleum, or electricity. Since electricity at these facilities is generated by some other energy source, when calculating the overall efficiency of the electrical process, the efficiency of the electrical generation process should be included. This is not done in this text. Efficiency factors can be applied to determine the overall efficiency of the electrical process.

some electrical energy for lighting, computers and HVAC. Core making and mold forming require some energy in the form of natural gas, electricity and compressed gas to form molds, bake and transport sand.

Raw materials enter the facility in the form of scrap metal or high-quality graded metal and are charged into the furnace. The molten material is poured into the mold and allowed to solidify. The casting is then shaken out of the mold by mechanical vibrations. The casting is transported to the finishing stages where runners are cutoff, parting lines ground down, and the surface is polished to meet the customer specifications. When necessary, the casting is heat treated to obtain the desired material properties. Support operations involve the transportation of sand, molds and castings. Although the melting operations use a variety of fuels, post-melting processes are powered by electricity, except heat treatment, which is typically fueled by natural gas.

The distribution of EUE that might be found at a metal casting facility is shown in Figure 2 for a hydrocarbon and an electrically powered metal casting company. This distribution of energy will depend on the type of furnace, charge material and other processes at the facility. Figure 2 gives a general view of the relative importance of various processes. Melting accounts for 20% to 80% of the EUE, while facility heating and afterburner clean up can account for 4% to 19% additional natural gas usage. At times, on-site heat-treating is

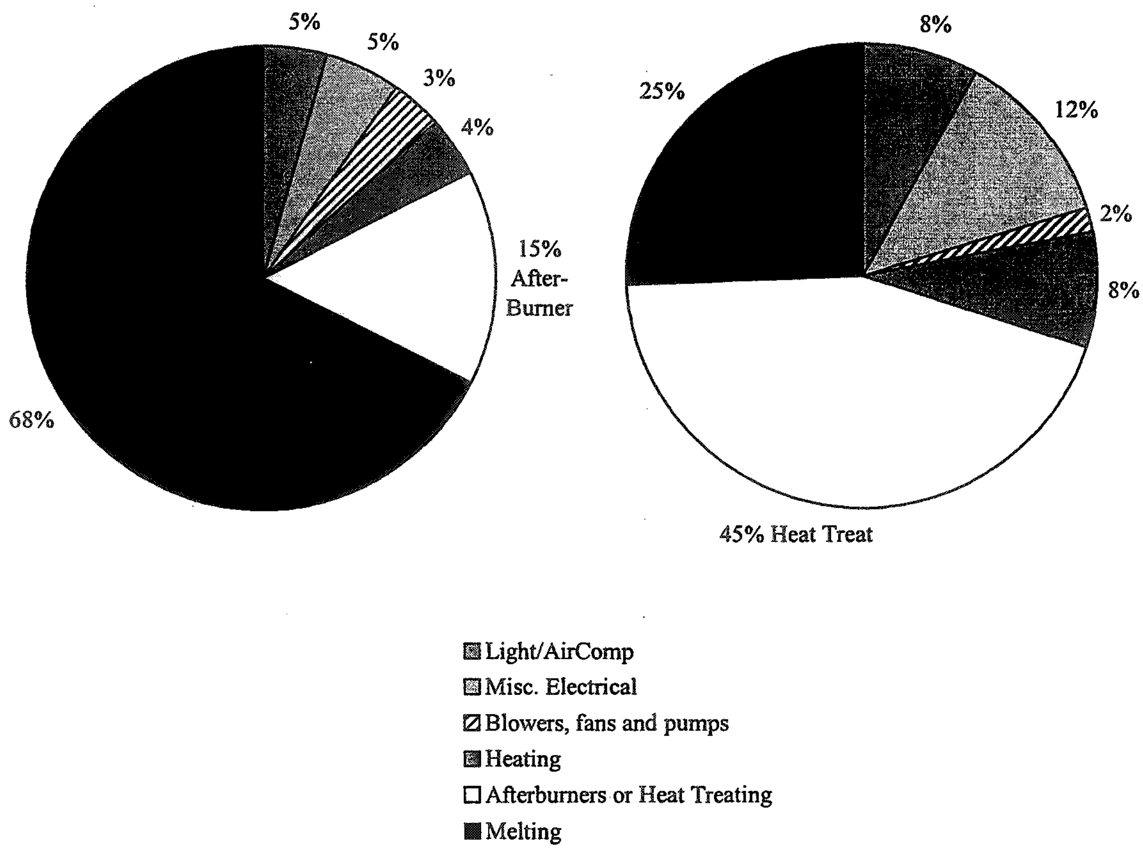

Figure 2. End Energy Usage (EUE) at Metal Casting Facilities

performed using a natural-gas powered furnace. accounting for a large percentage of the natural gas used. Lighting, air compressors, blowers, fans and pumps can account for 5% to 10% of the total EUE. Other electrical processes, including motors used in finishing operations and forklift batteries, will account for 5% to 15% of the EUE.

Melting represents a major fraction of the energy required by metal casting facilities and will be discussed first. Blowers, fans and pumps represent more areas these companies can improve operations and will be discussed second. Finally, ideas for combined heat and power are present as future possibilities.

Melting Efficiency

Melting constitutes a large portion of the energy requirements for metal casting facilities. A detailed review is important for identifying energy savings. Energy requirements will depend on the alloy, pour temperature, and furnace losses. Energy content in British Thermal Units per pound (Btu/lb) and pour temperatures for typical alloys are given in Table 2 (Reed 1997). It is interesting to note that although aluminum has a lower pouring temperature than brass, its high specific heat and heat of fusion result in higher heat content per unit mass than brass.

As the energy content and pour temperature increase, more thermal losses are expected since furnace temperatures and heat transfer rates would have to increase to meet a given melt flow rate. Higher furnace temperatures and fuel flow rates lead to larger wall losses from conduction, convection, and radiation. Other losses include those caused by holding molten metal prior to pouring, furnace cycling, and preheating equipment.

Table 2. Energy Content and Pouring Temperature of Various Metals

Metal	Energy Content at Pouring, Btu/lb	Average Pour Temp., °F
Aluminum Die Castings	481	1400
Aluminum	497	1380
Brass Castings	317.8	2250
Grey Iron Castings	583	2800
Steel Castings	626	2800

The furnace will require more energy to produce casting than just the amount indicated by the energy content. Added mass due to runners, risers and sprues force a larger amount of metal to be cast than desired. Much of the initial effort in laying out a pattern goes into minimizing these losses. The added mass also increases the amount of heat transfer required and as a result, the overall energy losses increase. Denoting the effectiveness of the metal casting process, r_m, as:

$$r_m = \frac{M_c}{M_t}$$

where M_c is the mass of good castings, and M_t is the total metal cast. The thermal efficiency of the furnace is:

$$\eta_{th} = \frac{M_t E}{EI}$$

where E is the energy content at pouring given in Table 2, and EI is the energy input into the furnace.

Heat transfer to the surroundings will reduce the thermal efficiencies for all furnaces in the same manner, however there are distinct differences in the thermal efficiencies expected between electrical and natural gas powered furnaces. Typically, a furnace powered by electricity should have a high thermal efficiency, η_{th}~1, since the thermal losses in generation and transmission would have occurred outside of the facility. However, as discussed below, thermal losses due to coil cooling will keep the furnace from achieving 100% efficiency. For natural gas furnaces, where the enthalpy of the exhaust gases can result in considerable thermal losses, it is desirable to achieve thermal efficiencies around 0.85. Defining operating efficiency as:

$$\eta_{op} = \frac{M_c \times E}{EI}$$

Operating efficiency is the thermal efficiency times the effectiveness of the casting process. It is desirable to maximize this quantity to achieve the highest energy performance from a furnace. Operating efficiencies of 25% to 65% were observed for induction furnaces and 3% to 25% for natural gas furnaces. Based on an industry standard r_m of 0.5, thermal efficiencies for electrical induction furnaces can be as low as 50%. Natural gas thermal efficiencies ranged from 6% to 50%.

Energy Usage shown in Figure 2 indicates that improving thermal efficiency is important for all furnaces. Achieving peak efficiency requires an understanding of the thermal cycles and heat losses that occur in a furnace. A number of references are available that identify furnace losses (Reed 1997; Thumann and Mehta 1997). Steady state losses occur from high temperature exhaust gases, furnace cooling water, furnace surfaces and infiltration of air into the furnace. Cyclic losses occur when a furnace is operated in a batch mode due to thermal inertia of the system. Even in batch mode, the transients are slow enough that heat loss and heat recovery processes can be analyzed in steady state, and integrated over the entire furnace cycle.

The maximum furnace temperatures control most of the steady state losses. As maximum temperature increases, the amount of energy lost increases as well. Exhaust-gases losses result from discarding the enthalpy content of the hot gases from the furnace. These losses are proportional to the exhaust (and furnace) temperature. In the case of induction furnaces, there are no exhaust gases losses; however, cooling water is provided for the coils and the heat transfer to the coils will increase with temperature. The heat loss through the sides and top of the furnace is driven by the temperature difference between the inner and outer wall of the furnace. Conduction to the outer wall carries heat from the furnace. Radiation and convection then heat the facility. Many of the facilities visited required no additional space heating during winter, but required cooling fans during summer, indicating that heat loss to the facility is substantial.

Exhaust Gas Heat Recovery

Exhaust gas heat losses are a significant portion of the energy required for heating, when using a hydrocarbon fuel source. Fortunately, in some cases heat exchangers can be used to recover these losses. Non-ferrous metal casting industries, and heat-treating facilities can utilize medium to high temperature heat recovery devices to recover exhaust gas losses. Foundries using hydrocarbon fuels such as natural gas and coke to make ferrous castings can typically recover heat using high temperature heat exchangers.

As shown in Figure 3A, natural gas furnaces draw fresh air for combustion from the surroundings and exhaust products of combustion at higher temperatures. The high temperature exhaust gases carry 20% to 40% of the energy away from the furnace. By installing a heat exchanging device such as a recuperator or regenerator, the energy from the exhaust gases can be recovered and transferred to the incoming fresh air as indicated in Figure 3B.

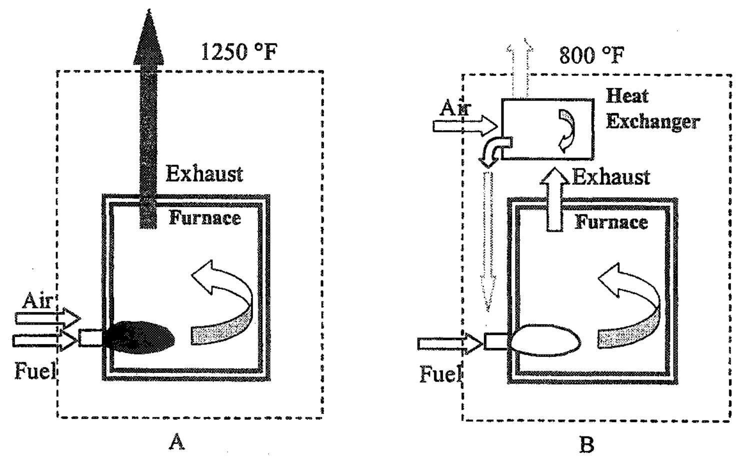

Figure 3. Furnace Operation Without (A) and With (B)

Recuperators and regenerators are two heat recovery devices that have been used in the past to improve furnace efficiency. A recuperator is a devices in which the heat is transferred by conduction and convection, typically through a medium separating the two flows. A regenerator is a device in which heat is exchanged by storing the energy in another medium and alternating the passage of hot products and cold air through the storage medium. The addition of either device will increase the pressure drop through the furnace, increasing the pumping power required by the combustion air blower.

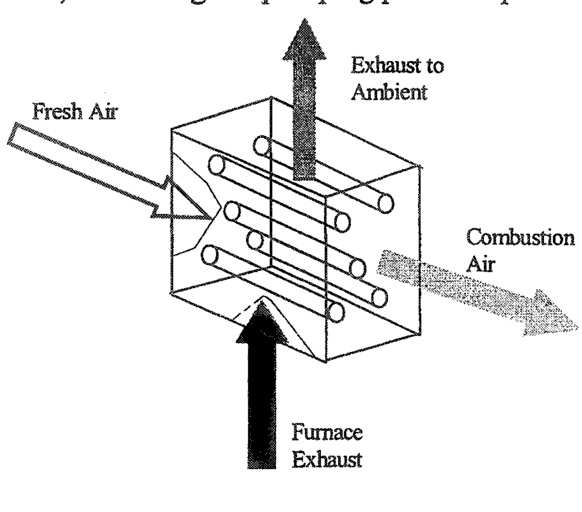

Figure 4. Cross-Flow Heat Exchanger

The recuperator can often be added to the furnace exhaust with a few modifications to the exhaust stack, air inlet and combustion air blower. A schematic of a cross-flow heat exchanger is shown in Figure 4. Hot gases exhaust vertically and fresh air is passed through tubes to the combustion chamber. The regenerator typically involves the added complexity of either moving parts or sequenced firing. Added controls, to improve the effectiveness of the heat exchanger, are desirable regardless of the heat recovery device used.

Standard burners are typically capable of handling preheated combustion air up to 400 to 600 °F, and up to 800 °F with modifications [Reed, 1997, 35]. Higher preheating is available with improved design burners and modified air handling equipment. The effect of preheating on the efficiency of the melting process is shown in Figure 5 for exhaust gases that are exiting the furnace at 1250 °F. The preheated combustion air temperatures are also indicated in Figure 5 as a function of the size of the heat exchanger. Heat exchanger size was calculated using a counter flow heat exchanger and complete combustion with 10% excess air.

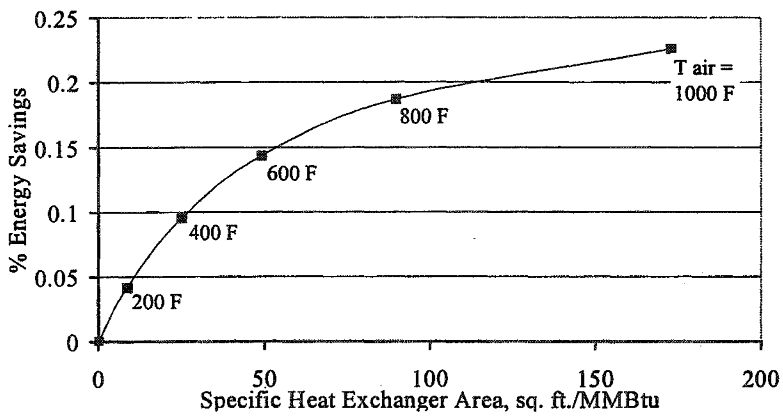

Figure 5. Energy Savings Resulting from Preheating Air

The heat exchanger size is important since the size will determine the cost of installation and the resulting savings that can be obtained. A company using natural gas for aluminum melting with melting energy accounting for 70% of the total energy usage, would see nearly a 14% energy usage decrease with the addition of roughly 100 sq. ft. of heat exchanger for each million Btu/hr of furnace input.

Recovering Thermal Loss From Electrical Induction Furnaces

Electrical furnaces do not have the exhaust gas losses that natural gas and coke-fired furnaces have, and consequently operate with higher thermal efficiencies. Higher efficiency is necessary since the furnace operates on an expensive energy source (electricity), which has generation and transportation losses associated with it. This section discusses aspects particular to the induction furnace.

An induction furnace operates by cycling the current through coils embedded in the furnace. This cycling induces a current in the charge material, heating it by internal resistance. The coils driving the induced current become hot due to heat conducting from the furnace and from internal resistance. Water is made to flow in channel through the coils to remove this heat and keep the coils within their operating temperature range. This results in creating a heat sink (the coils) that is close to the heat source (the melt). The coils are typically cooled by a water/glycol mixture and can represent a 20% to 30% energy loss (Energetics 1999, 42).

Although the energy from the coils is typically low temperature heat, below 200 °F, the amount of heat generated is substantial. Banks of air-cooled units outside the facility are required to cool the circulating water/glycol mixture. As shown in Figure 2, every company in this study had some facility heating requirement during the winter which could be meet by the heat rejection from the furnace cooling system. Mehta proposed a similar arrangement for low temperature heat recovery of spot welder cooling water (Mehta 2000).

Redirecting heated air from the water cooling units into the facility could meet the need for winter heating. For example, a 500 kW induction furnace operating with 20% energy losses would generate 100 kW (0.34 million Btu/hr) of heat. Typically, the only addition required at the facility is ductwork to redirect the warm air into the facility, or vent air to the outside during summer.

Other Thermal Losses

Reducing heat losses for conduction, convection and radiation are important for the efficient operation of all furnaces. Metal casting companies keep a constant vigilance on the furnace lining thickness and attempt to schedule repairs during downtime. The magnitude of the losses can be perceived due to the uncomfortable temperatures when standing close to some furnaces. At times these losses are a necessary evil. However, they should be avoided when possible through the use of sound engineering practices.

All three losses act together, so reducing one can positively affect the others. Increasing the furnace insulation thickness will reduce conduction through the furnace wall. This in turn will decrease wall temperatures, resulting in less convection and radiation losses from the exterior wall. An additional benefit of adding insulation is that often this plugs holes in the combustion chamber, reducing combustion gas losses and infiltration of air into the combustion zone. In many cases, burner orientation can also affect furnace surface temperatures, resulting in increased wall temperatures where flames impinge on the furnace wall. When possible, maintaining a uniform furnace wall temperature is desirable for minimizing wall losses.

An uncovered holding tank containing molten aluminum provides a good illustration of the energy savings from reducing losses due to radiation and convection. Typically die casting facilities use holding tanks at each casting machine. Molten material is added to the furnace, which is then ladled into the casting machine. As a result, no melting occurs in the tank and only a faction of the energy is used to bring the metal to casting temperature, the rest is loss to dross which is pulled off the surface of the metal, exhaust gas losses, radiation and convection. The holding tanks are uncovered to allow access for ladling material or charging, however there are large intervals of time when the tanks are idling.

Heat loss occurs at the open surface between the 1200 °F metal and the surroundings due to convection and radiation. Inside the tank, convection currents in the metal increase losses by forcing the hottest material toward the uncovered surface. From the molten aluminum surface at 1200 °F, the heat losses per unit area are given by the following equation:

$$\text{Heat Loss} = h \times (T_{surface} - T_{gas}) + \varepsilon\sigma\left(T_{surface}^4 - T_{surround}^4\right)$$

The convective heat transfer coefficient, h, for air is a function of the temperature and geometry, in this case estimated at 10 Btu/hr/ft^2/°F. The driving potential for this convection is the difference between the surface temperature, $T_{surface}$, and the gas temperature, T_{gas}.

The second term in the equation is the radiation heat transfer from the metal surface to the surroundings. The surface emissivity, ε, for molten aluminum is approximately 0.55 and the Stephan-Boltzmann constant, σ, is 0.1714×10^{-8} Btu/h/ft^2/°R^4. The driving potential is given by the difference between the surface temperature (absolute units) to the fourth power and the temperature of the surround walls raised to the fourth power.

For the case when the surrounding walls are 90 °F and the gas temperature is 70 °F, the estimated heat loss is 18,400 Btu/hr/ft^2, 60% of which is convection and 40% of which is radiation. By installing an insulated cover, the surface temperature will decrease to approximately 170 °F, and the emissivity will increase to 0.8. The resulting heat loss is 190 Btu/hr/ft^2, 50% due to convection and 50% of radiation. The energy requirements for heating an uncovered versus a covered three-foot diameter holding furnace are illustrated in Figure 6. Even though the radiation and convective losses have been reduced, the losses due to dross formation and high temperature exhaust gas losses are still large. The overall heat losses could potentially be reduced by 70%, depending on the furnace operations.

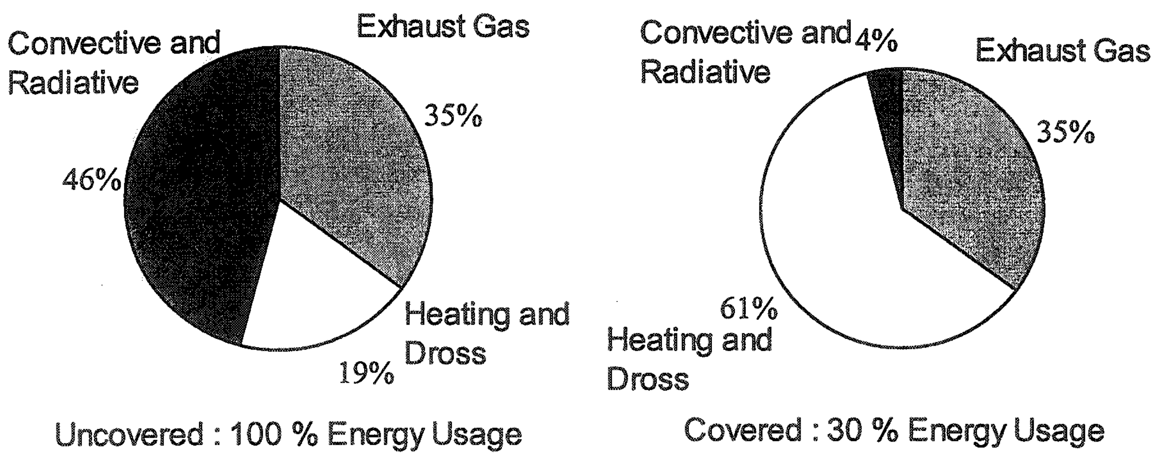

Figure 6. Energy Required for Heating Holding Tanks

Controlling Blowers and Fans

In most facilities, electric motors are used to drive for blowers, fans, and pumps. These devices are used to provide air for combustion, dust collection, and water circulation. The affintity laws govern the fluid mechanics for this type of machinery. These laws show that the horsepower required for moving air, in a large diameter duct at moderately high velocity (incompressible flow speeds), is proportional to Q^3, where Q represents the volume flow rate.

In most instances, an exhaust damper or a butterfly valve is installed downstream of the device to restrict the flow rate to the desired amount. This increased flow restriction will reduce the flow rate and the horsepower required, but will not achieve the reduction in power indicated by the affinity laws, due to the increased pressure drop. An alternative is the variable speed drive, VSD, which can be used to control the speed of the blower, reducing the volume flow rate without restricting the flow and allowing the motor to operate closer to the theoretical required power.

Understanding process requirements is important for installing variable speed drives in manufacturing facilities (Martin 2000). Actual savings will vary with the type of equipment currently installed. For example, a variable inlet vane would require less energy than an exhaust damper (Boggs 2000, 12). In many cases, a VSD can be used to control motors for large fans and blowers used in some metal casting facilities.

An example of the energy savings achievable with a VSD installation is given in Figure 7 for a 300 hp blower providing combustion air to a cupola furnace. The volume flow rate of combustion air changes from shift to shift with production changes as noted in Table 3. The volume flow rate of air is controlled by an exhaust damper system that restricts the flow rate of air, without significantly changing the power consumption of the motor. As indicated in Table 3, the volume flow rate Q changes from 8000 cfm to 6500 cfm while the power consumed by the motor changes from 300 hp to an estimated 288 hp based on information from typical blower curves.

Energy savings will result from operating the motor closer to the required power and not restricting the flow and will also reduce motor and valve wear. Figure 7 and Table 3 indicate the motor horsepower required for different volume flow rates with a VSD. At full flow rate, 8000 cfm, 300 hp is required with and without the VSD. The VSD power curve is given by the affinity laws and quickly diverges from the original motor's power curve.

The reduction in power is indicated by the difference between the current and VSD horsepower. The energy savings are the power savings multiplied by the time spent at each flow rate. When the 300 hp motor is operated on a schedule of 24 hrs/day, 7 days/wk, 52 wk/yr, a total of 536,000 kWh/yr in energy savings can be expected. Various manufacturers estimate the drive cost as $35,000, while installation costs are estimated to be $15,000 (Stebbins 1998). At a cost of $0.05/kWh for electricity, the simple payback period for installing a VSD is under 2 years.

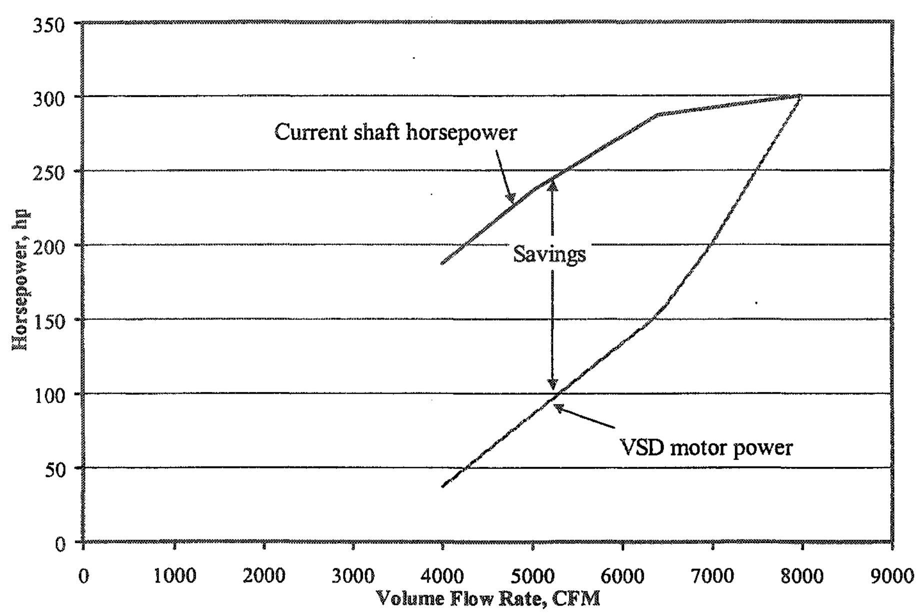

Figure 7. Horsepower Required for Moving Combustion Air

Table 3. Operational Schedule and Power Required Without and With VSD Installed

Shift	Duration	Volume flow rate	Current Power Usage	VSD Power
1	7 hrs	8000 cfm	300 hp	300 hp
2	7 hrs	7000 cfm	292 hp	201 hp
3	7 hrs	6500 cfm	288 hp	161 hp
Change over	3 x 1hr	4000 cfm	188 hp	38 hp

Combined Heat and Power (CHP): Thermal Reclamation

With the recent changes in the electrical power industry, some metal casting facilities may choose to take control of their electrical power supply and install equipment for on-site power generation. Typically, the generation of power on-site is by natural-gas turbine, gas engine or diesel engine. The electrical generating efficiency of these devices is between 25% and 40%, with the balance of the energy carried in the exhaust. For example, consider a facility operating a 3-megawatt (MW) gas turbine to generate electricity to its electrical furnaces. For a turbine with 30% efficiency, approximately 10 MW of natural gas must be supplied to generate the electrical power. The energy cost to the facility to generate this electricity would be $0.06/kWh for a natural gas cost of $5/million Btu. If this cost is cheaper than the price of electricity, the facility may want to consider installing the turbine. However, maintenance costs and connection charges would increase the cost of generation. Combining the generation of power and utilizing the heat elsewhere would then make sense in reducing the cost of operation.

A possible location for recoverying the energy in the exhaust gas is the sand reclamation process. Many facilities operate a thermal sand reclamation unit where the spent cast sand is heated to a temperature that volatilizes and destroys the resin binders. If a facility operates a natural-gas powered sand recovery unit, the amount of energy provided by the turbine is typically larger but at a lower temperature (800 °F) than that needed (1200 °F) by the sand reclamation unit.

The exhaust gases would provide enough energy to preheat the sand reclamation combustion air to 800 °F, resulting in savings of 14%, assuming an exhaust temperature of 300 °F from the sand reclamation unit. The balance of the exhaust gas energy could be used to heat the sand itself, preheating prior to reclamation. The efficiency of the overall system will depend on the flow rate of sand and the final desired temperature of the sand.

Conclusions

Methods for reducing energy use at metal casting facilities have been presented. Specific examples have been used to illustrate the potential for increase productivity through energy efficient technologies.

For companies burning hydrocarbons directly:

- Heat recovery of the exhaust gases reduced primary fuel costs.

For electric furnaces:

- Low temperature heat losses were recovered for facility heating.

For all facilities:

- Sufficient insulation and covering hot metal reduced energy costs.
- Optimizing blowers, fans and pumps increased electrical energy efficiency.
- By thoroughly analyzing the facility's thermal and electrical needs, opportunities for CHP were identified.

The actual savings for a facility will depend on operations and equipment. Quantifying the energy balance of the facility will allow a company to identify the most cost effective route to energy efficiency.

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