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WASTE HEAT RECOVERY FOR INVESTMENT CASTING FURNACES

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Waste heat recovery for investment casting furnaces is an effective method to lower BOTH operating costs and emissions.

COMBUSTION

Combustion is the rapid mixture of oxygen with a fuel, resulting in the release of heat and gaseous byproducts called flue gases. Flue gases are mostly composed of carbon dioxide and water in the case of a hydrocarbon fuel such as natural gas, propane or fuel oil. While heat is the desired product of combustion for our purposes, carbon dioxide is an unavoidable byproduct having increasing importance to all industry. (At this point in the discussion, it shall suffice to understand that the release of carbon dioxide is in direct proportion to the heat released.)

The oxygen required for combustion comes from the atmosphere, and is a mixture of gases nominally composed of 78 percent nitrogen, 21 percent oxygen and the remaining one percent trace elements. While nitrogen is an important element in the chemistry of natural and industrial processes, the molecular nitrogen contained in the atmosphere is, for the purposes of explaining the fundamentals of combustion, essentially inert. The nitrogen is just a parasite going along for a free ride on the back of the combustion process. A significant portion of the heat released in the combustion process is imparted to the nitrogen, which leaves the process in the flue gases.

In order to quantify how much heat our process requires and how much fuel we will need, we must know what heat is and how to measure it. Heat is the thermal form of energy. We can all feel the difference between a hot surface and a cold surface, but how do we quantify that difference? Let us accept the fact that the hotter surface releases more heat (energy) than the cold surface, and let us accept the fact that heat is transferred from objects having more heat to objects having less heat.

To quantify the ability (potential) of an object to transfer heat to other objects, we use the familiar units of temperature such as Celsius or Fahrenheit. To quantify the amount of heat transferred between bodies we use units of energy such as kilocalories or BTUs (British Thermal Units). FYI: One BTU is the amount of heat required to raise one pound of water at 59°F to a temperature of 60°F.

Fuels contain energy stored in the chemical bonds of their constituent molecules. Industrial fuels are selected and produced to provide a very specific amount of energy. The typical natural gas in the United States is composed of approximately 90 percent methane, 5 percent ethane and contains about 1000 BTU per standard cubic foot (SCF - a standard cubic foot is measured at sea level and 60°F).
If your furnace is rated at a maximum of 2 million BTU/hr, you may now calculate that your furnace will consume up to 2000 SCF of natural gas per hour. FYI: your gas supplier prefers to measure your gas usage in units of energy called Therms. A Therm is 100,000 BTU.

In order to release all of the energy stored in our fuel, we need to burn it completely. From the basic definition of combustion, we know that we need oxygen, but how much? Let us accept the fact that it takes about ten cubic feet of air to provide enough oxygen to completely burn one cubic foot of natural gas, and let us also agree that one cubic foot of air will provide for the release of 100 BTU. If your furnace is rated at a maximum of 2 million BTU/hr, you may now calculate that your furnace will consume up to 20,000 SCF of air per hour.

Up to this point, we have discussed the ideal air-to-fuel ratio of approximately 10 to 1. There are limits to how widely this ratio can vary based upon what type of burner equipment is selected, but as a general rule, modern combustion systems will operate safely and reliably with air-to-fuel ratios that provide a condition with slightly too much fuel (rich) to a condition that provides an excess of air (lean). If 50 percent more air than what is ideally required is supplied we commonly referred to this condition as “50% excess air”. Fifty percent excess air will leave about 7.5% oxygen remaining in the flue gases. The presence of excess air can be of crucial importance in furnaces for investment casting because excess air is frequently relied upon to provide for the incineration of wax in the molds.

AVAILABLE HEAT

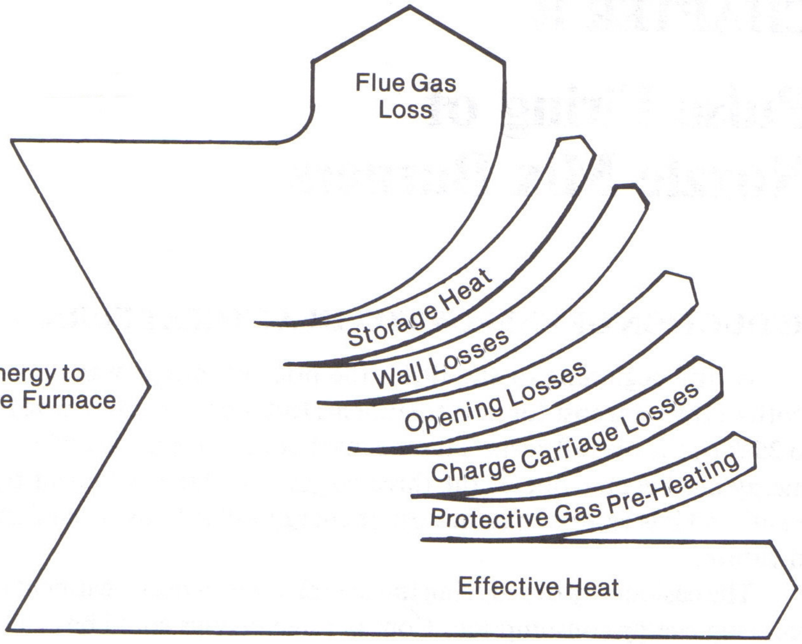
The simplest way to heat ceramic molds would be to direct the hot gases from combustion directly onto them, but obviously much of the heat will be lost into the atmosphere around the molds. An insulated enclosure must be built to surround the molds with the hot gases, preventing the molds from losing heat to the atmosphere and directing the flue gases away from the process. This enclosure is called a furnace.

Let us build a furnace and test it by placing 2000 pounds of alumina ceramic molds at 60°F into this furnace and heating them up to 2000°F in one hour. Additionally, our ceramic mold expert has requested that the atmosphere inside this furnace have at least 6% oxygen, so we will adjust our air-to-fuel ratio to include more air than is ideally required – about 37% excess air. We know the heat capacity (specific heat) of our mold material and so we are able to calculate our energy requirement for this test – the molds require 741,080 BTU to reach 2000°F in one hour. We start the furnace and monitor the temperature, but the molds do not reach temperature for over 3-¾ hours! We know that no insulation is perfect, but our furnace has the best insulation with a low heat capacity and a low thermal conductivity. What happened?

Let us repeat our test. This time we will measure the temperature of the exterior of the furnace and the temperature of the waste gases leaving the flue as well as the temperature of the molds – what goes in must come out. Throughout the test we note that the temperature of the waste gases leaving the flue are always higher than the temperature of the molds and we note that the temperature of the exterior of the furnace is never higher than 150°F. In fact, as the molds approached 2000°F, the temperature of the waste gases approached 2200°F! Why is so much heat leaving the furnace but not entering our molds?

Our simplistic approach to combustion and heat did not account for something. We correctly calculated the heat requirement for our molds. We correctly calculated the required air-to-fuel ratio. We correctly assumed that all of the energy in the fuel would be released into the combustion gases, but we erroneously assumed that all of the energy from the combustion gases would be released into the furnace. It seems that our furnace is not 100 percent efficient. If we review our combustion fundamentals, it seems we forgot to calculate how much heat would be required to raise our fuel and air up to the waste gas temperature of 2200°F.

Fortunately, the problem of quantifying combustion efficiency was examined and solved over 100 years ago. Through previous experiments and calculations by others we know that at best, only 26.4 percent of the energy going into our example furnace is available to heat that load of ceramic molds to 2000°F in an atmosphere of 6 percent oxygen, while at least 73.6 percent of the energy is lost to heating the incoming gases. Theses values are derived from a calculation that subtracts the heat lost to the waste gases from the gross input of heat resulting in a value called *"Available Heat"* which is frequently expressed as a percentage in tables, graphs and computer programs. A simple graphic tool called a *"Sankey diagram"* was developed to help us conceptualize the overall efficiency of a heating system, including all loses, not just flue losses (see example diagram below).



Sankey diagram

If 75 percent more air than what is ideally required (about 9.5% oxygen in the flue gas) is supplied into the furnace, only 11 percent of the heat would be available to heat the load and 89 percent of the heat would go up the flue! In fact, if 125% excess air (about 12% oxygen in the flue gas) was provided, it would be impossible for the molds to reach 2000°F because the temperature of the combustion gases would be diluted to 1992°F and would have no available heat left to release as the product approached 1992°F. While operating a combustion system at the ideal air-to-fuel ratio will provide the best possible efficiency under any condition, it is sometimes necessary to operate a combustion system at other than the ideal ratio due to other process requirements. For investment casting furnaces, excess air operation – and therefore low efficiency - is the “norm”.

WASTE HEAT RECOVERY

Waste heat recovery is a process that puts to use heat which would otherwise be wasted. Using the example of our simple furnace, we could duct the waste gases to another insulated enclosure in order to further utilize the heat in those waste gases. By placing cold molds in this auxiliary chamber, we can preheat them to a temperature below the final temperature of our furnace and then transfer them to our furnace once the first batch of molds have finished heating. The waste gas exiting the preheat chamber will be lower than when it entered the preheat chamber and thus heat will have been extracted. This process of preheating and heating can continue as long as there is work to be heated. This is a very old idea and has great merit; however it is suitable only for batch processing and requires additional handling of the molds.

A similar concept for preheating molds utilizes a continuous process in a “tunnel” type furnace extending the length of the tunnel to accommodate more molds while ensuring that the waste gases travel the entire length of the furnace, exiting at the end where the cold molds are charged. This is also a very old idea and has great merits; however, it is suitable only for continuous processing.

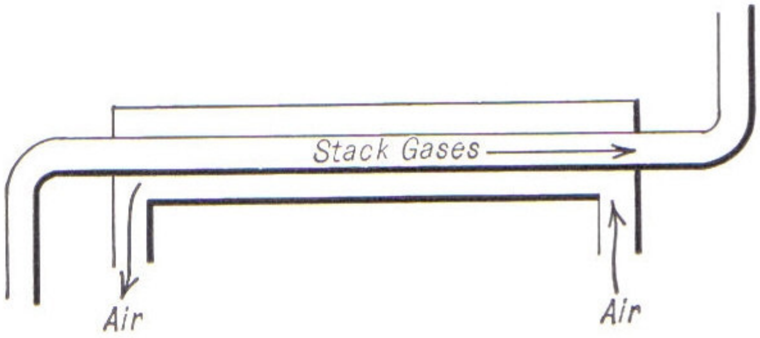
Note that both methods of heat recovery described above act directly upon the product to be heated. This form of heat recovery is called *“Direct Recovery”* or “load recovery”. Direct recovery is conceptually simple but has some limitations. Direct recovery is best incorporated into new heating systems while they are on the drawing board, rather than retrofitted to existing processes due to the required changes to the physical footprint of the existing equipment. Also, the effectiveness of direct recovery can be affected by production schedules that do not always utilize the preheating zones of the furnaces for the majority of the operating time. There is no point in having a preheating chamber if it will be empty most of the time.

Is there a way to utilize the waste heat that does not have the limitations of direct recovery? Consider the heating process as a *system*: What goes into the system must balance what comes out of system. If the air and fuel could be heated by the waste gases before burning, the waste gas temperature would be lowered, giving higher efficiency. This form of waste heat recovery is referred to as *“Indirect Recovery”*.

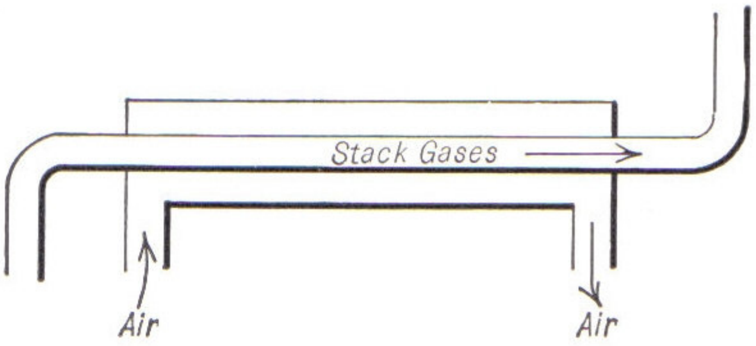
This is exactly the solution envisioned and successfully implemented by Sir William Siemens in the 1850’s. In Sir Siemens’ design, pairs of large chambers filled with firebrick checker-work alternately absorb the heat from the outgoing waste gases and then release it to the cold incoming air and fuel by alternately passing these gases through the chambers via valves and ducts in a timed sequence. These refractory-filled chambers are called *regenerators*. Unfortunately, these *regenerative heat exchangers* are large, complex and function in a cyclical manner. Some continuous regenerators have been developed and applied with limited success, but mostly for low temperature processes.

Having proven that a *heat exchanger* is a practical way to recover waste heat from furnaces, engineers set about making improvements. The most significant improvement in heat exchangers for waste heat recovery was the development of the recuperator. The recuperator exchanges heat continuously *through* a barrier material so that the waste gases and the gases to be heated never pass through the same volume and always remain separated. The first recuperative heat exchangers were made of refractory materials, but as heat resistant metals became available, recuperator design progressed rapidly. Additionally, as fuels of higher value (natural gas and fuel oil) became widely available, it no longer became necessary to preheat the fuel to achieve significant improvements in efficiency, and so the modern recuperator has become almost exclusively an air heater.

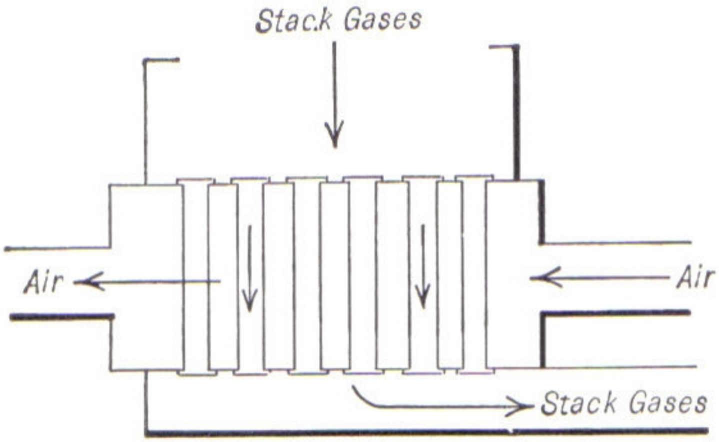
Recuperators may be divided into three classes according to how the gases move through them; counter-flow, parallel-flow and cross-flow (see diagrams below). Each has its own advantages and disadvantages. The counter-flow recuperator provides the highest possible preheat temperature, but may require more expensive materials or components to prevent over-heating. The parallel-flow recuperator provides the lowest possible preheat temperature, but may allow for lower cost construction if less expensive materials or components are required. The cross-flow recuperator allows for a maximum amount of heat transfer area in a compact and economical unit. Combinations of the three classes have been utilized to produce a recuperator having the desirable characteristics of more than one class.



COUNTER FLOW TYPE



PARALLEL FLOW TYPE



CROSS FLOW TYPE

Also note that there are different types of recuperators, not based solely upon gas flow pattern, but upon shape, predominate mode of heat transfer, materials of construction, etc. For example, you may see a "bayonet type" recuperator with combination cross-flow/parallel flow arrangement. One company may refer to their "canal type" recuperator while their competition offers a competitive model called a "flue type" recuperator. You may consider a "stack type" or a "radiation" recuperator. These terms, while descriptive in some way, still describe recuperators that work on principles of the three classes already described.

We have discussed direct recovery, indirect recovery in the description of waste heat recovery, a third form of waste heat recovery exists - *Secondary recovery.* Direct recovery and indirect recovery both aim to keep waste heat within the heating system itself. Secondary recovery utilizes the waste heat from one heating system to supply heat to another heating system.

For example, the waste gases from furnaces in steam hammer forge shops were frequently passed through a boiler to produce steam to operate the hammers. It is usually advantageous that the system benefiting from the waste heat and the system producing the waste heat are allied processes – i.e. one process does not work without the other. When carefully implemented, secondary recovery can be quite beneficial to the operation of an entire process line or production facility, but it also requires complete integration and reliance upon all parts of the process line or production facility to realize full utilization of the waste heat.

ECONOMIC CONSIDERATIONS

By definition, heat is energy. We must buy energy, whether it is electricity, natural gas, or gasoline. When we waste energy, we waste money. Waste heat recovery reduces waste and therefore saves money.

When energy was cheap and plentiful, energy savings meant very little to the average manufacturer who could save large amounts of money by investing in process improvements such as automation and statistical process control, achieving greater productivity and/or producing less waste product. At the time, this was correct business planning because money was invested into projects that would provide the greatest *return on investment*. It is quickly becoming the case that energy is one the greatest costs in manufacturing processes that involve heating and it now makes sense to evaluate heating costs to determine if the return on investment provided by waste heat recovery is worthwhile.

Also, a further economic consideration regarding the use of energy is developing at this very moment – *carbon emissions*. The Clean Air Act of 1970 has been revised and amended several times, but the undeniable future of emissions legislation will be to regulate carbon emissions in general. As we noted in the fundamentals of combustion, the release of carbon dioxide is directly proportional to the heat input. When heat is wasted, excess carbon dioxide is produced. Soon, when we waste energy, we will be wasting carbon and then we will waste *more* money

The first step to determining the praiseworthiness of a heat recovery installation for any facility is to gather all of the existing process data for the heating system(s) of concern:

- ☐ Hours of operation per day, per week, and per year
- ☐ Operating temperatures or temperature profiles
- ☐ Flue gas excess oxygen or excess oxygen profile
- ☐ Weight of wax/plastic to be consumed per mold, per hour
- ☐ Input (BTU) rating of equipment
- ☐ Fuel usage per month and per year
- ☐ Average annual fuel price

Given this information, it will be possible to calculate the savings provided by the installation of heat recovery equipment.

The following two case studies and associated calculations are based on past projects completed by Armil/CFS.

CASE STUDY: BATCH BURNOUT AND PREHEAT FURANCE

Let us return to our ceramic mold heating furnace for an example of how the savings from waste heat recovery may be determined. Remember that the molds themselves required 741,080 BTU in one hour, but based upon our air-to-fuel ratio and our flue gas temperature, only 26.4% of the heat from the fuel was available given the operating temperature, so we really should supply (741,080 BTU/hr) X (100% / 26.4%) = 2,807,122 BTU/hr. *It is vitally import to know the flue gas oxygen level and waste gas temperature in order to find the available heat used in these calculations.*

Before we can put our example furnace into production, we must include an essential component that was not previously discussed for the sake of simplicity. The ceramic molds that the furnace is heating have been formed by the lost wax process and still contain some wax, even after the molds have been through an autoclave to remove the wax. In order to comply with emissions regulations and to prevent possible fire damage to the building, the flue gases must first be directed through a separate, insulated, temperature controlled chamber called an *afterburner*. The purpose of the afterburner is to provide, time temperature and oxygen to consume any unburned wax in order to prevent both the formation of smoke and the combustion of wax in the stack.

Based upon the heat requirements of the load and the assumption that no more than 1% of the weight of the molds is wax, we will supply 1,500,000 BTU/hr with 50% excess air to the afterburner. In accordance with local emissions regulations, the afterburner will be set to maintain at least 1650°F at all times, but as the furnace temperature rises above 1650°F we can expect the flue gas temperature to rise to 1850°F.

It should be noted that the available heat of 26.4% for the furnace still applies, but the analysis of the furnace-afterburner system may be simplified based upon the analysis of the final flue products. Based upon proportion, we will have a final flue gas oxygen content of 6.5%. Given the 1850°F flue gas temperature and the 6.5% oxygen level, we know that our overall available heat for our burnout and preheat furnace will be 36.6%.

Our example furnace operates for 16 hours per day, five days per week, 48 weeks per year, for a total of 3840 hours per year. Based upon production constraints other than the time required to heat the molds, it is not possible for the furnace and afterburner to operate at their respective full heat inputs of 2,807,122 BTU/hr + 1,500,000 BTU/hr = 4,307,122 BTU/hr, because, as the molds heat up to the final temperature, less heat is required to maintain the desired process temperatures. The furnace and afterburner will be equipped with automatic controls to adjust the heat input to match the heat requirements of the process, and so simply multiplying the maximum heat input by the total hours of operation will overestimate the fuel usage.

Our example company wisely installed a gas meter on this furnace over a year ago, and so an actual total for fuel used is available: 16,539,348 SCF of fuel has been consumed in one year of operation. This number seems reasonable because it is what would be expected if the furnace ran at about 1/2 of the total maximum available heat input for the scheduled hours of operation. Assuming the natural gas fuel contains 1000 BTU/SCF then 16,539,348 SCF = 165,393.48 Therm (remember that 100,000 BTU = 1 Therm). The average price of the natural gas fuel purchased over the past year was $0.75 per Therm and so the annual fuel cost was (165,393.48 Therm) X ($0.75) = $124,045.11.

Given all of the operating data and a calculation of our current costs, let us consider the possible savings that could be realized by adding a waste heat recovery to our example furnace. Our example furnace is constructed of materials and components that will allow the air to the burners to be as hot as 800°F, so if we can recover the waste heat we must keep in mind that this temperature is what will limit how much heat we can recover.

Assuming a combustion air temperature of 800°F, a flue gas temperature of 1850°F with a 6.5% oxygen content, we will find that the available heat under these conditions is 54.9%. In order to find the percent fuel saved with 800°F combustion air operating condition versus the previous 60°F combustion air operating condition, we perform the following calculation:
100 X [1 – (percent available heat with cold air) / (percent available heat with heated air)] =
100 X [1 – (36.6%) / (54.9%)] = 33.3% fuel saved. The previous annual fuel bill of $124,045.11 for the 60°F combustion air operating conditions multiplied by the 33.3% fuel savings for the 800°F combustion air operating conditions reveals a annual cost savings of $41,348.37 with waste heat recovery.

The next step to determining if waste heat recovery is worth consideration is not so much an engineering problem as it is an accounting problem. Two other factors must be considered: The desired time period for a return on investment and the cost to incorporate the waste heat recovery into the production process. The first factor - return on investment - is usually determined at the corporate management level, and is given as a simple time period, typically in months or years. The second factor is determined by heat recovery equipment manufacturers and/or furnace service contractors and/or furnace original equipment manufacturers.

The choice of the heat recovery equipment itself is typically determined by the application requirements. In the case of our example furnace, we know all the operating parameters and the construction details of the existing furnace, and so our options are limited to a heat recovery device sized to provide up to 800°F preheated combustion air for a heat input of 4,307,122 BTU/hr with 6.5% oxygen in waste gases up to 1850°F. If it was the case that the decision was between purchasing a new furnace without waste heat recovery or a new furnace with waste heat recovery, more heat recovery options would exist and these should be discussed with the original equipment manufacturers who will be quoting the equipment.

It is vitally important that heat recovery equipment manufacturers, furnace service contractors and furnace original equipment manufacturers supplying equipment or services be qualified in this particular field of heating. Investment casting furnaces operate with unique conditions – some more like an incinerator than a furnace. These suppliers should be able to demonstrate experience with similar projects.

Let us assume that our example company has a return on investment requirement of two years for energy efficiency and emissions reduction projects. Our example project manager has obtained three quotes for a turnkey retrofit of heat recovery onto our example furnace: One quote was lowest but unacceptable for reasons of experience, one quote was the highest with the longest delivery time, and one quote appeared to be just right at $60,000. Dividing the quoted project cost by our calculated annual fuel savings we see that we do meet our company's return on investment expectations: ($60,000) / ($41,348.37 / year) = 1.5 years.

CASE STUDY: PUSHER BURNOUT AND PREHEAT FURANCE

Another example for application of heat recovery to an investment casting furnace may be seen in a case study of a pusher-style continuous burnout and preheat furnace. The company wishes to increase capacity with the addition of a new automated investment casting line. A pusher furnace will provide the most efficient delivery of molds to the casters and so this type of furnace is chosen.

The molds still have some wax in them so this must be taken into account. It is decided that this relatively long furnace can incorporate internal incineration, eliminating the afterburner chamber. This combustion gas flow pattern disallows the use of the direct heat recovery typically employed in pusher furnaces, however, indirect heat recovery may still be considered.

The process requires the molds to be heated to 2100°F in an atmosphere of at least 6% oxygen. We establish that the available heat without heat recovery will be 22.9%. We establish that the furnace will operate for 8000 hours per year. We calculate the average heat input to be 2,500,000 BTU/hr. We establish that the average annual fuel cost will be $.90 per Therm and so we calculate that the annual fuel cost will be $180,000.

For budgetary reasons, it is decided that combustion air temperature of the heat recovery system will be limited to 800°F and we find that available heat with 800°F preheated combustion air is 40.7%. We now calculate a fuel savings of 43.7% for an annual cost savings of $78,722. The price add on to the new furnace for the addition of the heat recovery equipment has been quoted as $75,000, and so we calculate that the return on investment will be about one year, falling within the company's two year requirement.

We see that heat recovery is worth consideration for our example company. If our example company wishes to increase capacity through the purchase of additional furnaces, the integration of heat recovery equipment would also be worth consideration. An added benefit to purchasing new furnaces with integrated heat recovery equipment is that the new equipment may be designed to accept higher air preheat temperatures resulting in even greater savings.

FINAL THOUGHTS

Waste heat recovery has been successfully utilized in the steel industry for over 150 years. There is no better time than right now for a greater adoption and utilization of waste heat recovery within the investment casting industry.