Technical Notes

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Thermal Efficiency Limits for Furnaces and Other Combustion Systems

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Nomenclature

AF	=	stoichiometric air/fuel ratio on a mass basis
C_{paf}	=	gas specific heat for calculating the adiabatic-flame temperature, Btu/lbm°F
C_{pex}	=	exhaust-gas specific heat, Btu/lbm°F
E	=	excess air or excess oxygen
h_{oxy}	=	energy required to produce oxygen, kWh/ton
h_p	=	product enthalpy, Btu/lbm
h_v	=	fuel heating value, Btu/lbm
$\dot{m}_{\mathrm{ex}}$	=	exhaust-gas mass flow rate, lbm/h
$\dot{m}_f$	=	fuel mass flow rate, lbm/h
$\dot{m}_{\mathrm{max}}$	=	maximum product or feedstock mass throughput (often the design throughput), lbm/h
$\dot{m}_P$	=	product or feedstock mass throughput, lbm/hr
OF	=	stoichiometric oxygen/fuel ratio on a mass basis
q_{ex}	=	exhaust-gas losses (flue gas losses) or stack losses, Btu/h
q_{in}	=	total energy going into the furnace, Btu/h
q_p	=	energy going into the product or feedstock, Btu/h
q_w	=	wall, infiltration, dilution, and radiation losses, Btu/h
SE	=	specific energy, Btu/lbm
$\mathrm{SE}_{\mathrm{min}}$	=	minimum specific energy, Btu/lbm
T_a	=	ambient temperature used as the reference temperature, °F
T_{af}	=	adiabatic-flame temperature, °F
T_{ex}	=	exhaust-gas temperature, °F
T_{oa}	=	oxidant preheat temperature, °F
T_p	=	product or feedstock temperature, °F
α	=	energy efficiency criterion
η	=	thermal efficiency
η_a	=	ambient efficiency
η_c	=	Carnot efficiency
η_{ef}	=	electric heater efficiency
η_{eg}	=	electric generator efficiency
η_{max}	=	maximum efficiency
η_{oxy}	=	η_a or η_{max} using oxygen
η'_{oxy}	=	η_{oxy} corrected for the energy required to produce the oxygen
η_{PP}	=	power plant efficiency

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Introduction

THE United States industrial sector consumes 32.6 quadrillion British thermal units per year, over one-third of the total energy use in the United States [1], with a value of $100 billion. Of that amount, 60% is consumed in fossil-fired systems such as furnaces, boilers, and lehrs, with varying energy losses. Thermal efficiencies can range from over 90% for condensing boilers to under 10% for small batch-operated high-temperature furnaces. These devices can be improved, but what, if any, efficiency limits exist is not clear. For heat engines, the gold standard has always been the Carnot efficiency, which limits the maximum efficiency achievable based on just the hot and cold temperature reservoirs. This Note derives a similar expression for combustion systems and also shows the minimum specific energy possible and the condition in which it can be realized. The term furnace is used for convenience throughout this Note and it includes any device that transfers heat from a high-temperature source to a colder product, also referred to as a process heater.

Minimum Energy Analysis

Figure 1 shows a schematic of a steady-state operating furnace with the energy components entering and leaving the furnace. Thermal efficiency is defined as the energy going into the feedstock divided by the total energy going into the process. The maximum thermal efficiency is determined by reducing each energy term to its minimum theoretically possible value. In addition, when appropriate, more restrictive practical limits are also imposed.

The thermal efficiency is

$$\eta_a = \frac{q_P}{q_{\mathrm{in}}} \tag{1}$$

An energy balance yields

$$q_{\mathrm{in}} = q_w + q_P + q_{\mathrm{ex}} \tag{2}$$

where

$$q_{\mathrm{in}} = \dot{m}_f h_v \tag{3}$$

$$q_{\mathrm{ex}} = \dot{m}_{\mathrm{ex}} C_{\mathrm{pex}} (T_{\mathrm{ex}} - T_a) \tag{4}$$

where the specific heat values are calculated as the integrated average between the temperature of interest and the reference temperature.

The wall losses q_w are assumed to be negligible, which implies a well-insulated furnace. Equation (1) is then

$$\eta_a = \frac{q_P}{q_{\mathrm{ex}} + q_P} \tag{5}$$

The exhaust mass flow rate is the sum of the oxidant and fuel flow rates, which are related by the stoichiometric oxidant/fuel ratio (assuming that the furnace is well sealed):

$$\dot{m}_{\mathrm{ex}} = \dot{m}_f [1 + \mathrm{AF}, \mathrm{OF}(1 + E)] \tag{6}$$

The oxidant/fuel ratio is related to the adiabatic-flame temperature:

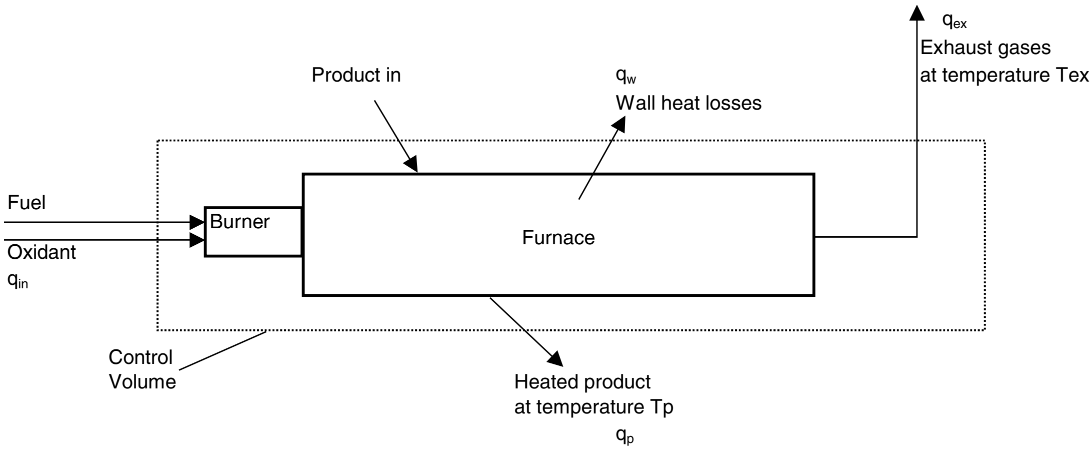


Fig. 1 Process schematic.

$$(T_{\mathrm{af}} - T_a) = \frac{h_v}{[1 + \mathrm{AF}, \mathrm{OF}(1 + E)]C_{\mathrm{paf}}} \tag{7}$$

Combining Eqs. (3), (4), (6), and (7) into Eq. (5),

$$\eta_a = 1 - \frac{C_{\mathrm{pex}}}{C_{\mathrm{paf}}}\frac{(T_{\mathrm{ex}} - T_a)}{(T_{\mathrm{af}} - T_{a)}} \tag{8}$$

The maximum thermal efficiency occurs for a reversible process, which requires an infinitesimally small temperature difference during heat transfer. This can be achieved by assuming that the furnace consists of a large number of small furnaces in series with the product passing from one to the other. The outlet gas of one becomes the inlet gas of the next downstream small furnace. As the furnace's horizontal size is reduced, the number of small furnaces increases. In the limit of zero size, the number of furnaces approaches infinity and the temperature difference and heat transfer between each furnace and the load approaches zero. Because the product throughput also decreases as the furnace size is reduced, an infinite number of each of these infinite sets of small furnaces are required to produce a finite amount of product. Because the temperature difference entering and leaving each furnace approaches zero, the specific heats in Eq. (8), which are only a function of temperature, cancel and the thermal efficiency becomes

$$\eta_a = 1 - \frac{(T_{\mathrm{ex}} - T_a)}{(T_{\mathrm{af}} - T_{a)}} \tag{9}$$

This is the highest possible thermal efficiency for any heating device with the temperatures given. The efficiency is widely applicable and is independent of the process or whether a change of state occurs because only the flame, exhaust, and ambient temperatures appear. It applies universally to any fossil-fired device that transfers heat to a load such as glass-melting tanks, aluminum smelters, ovens, kitchen stoves, or boilers.

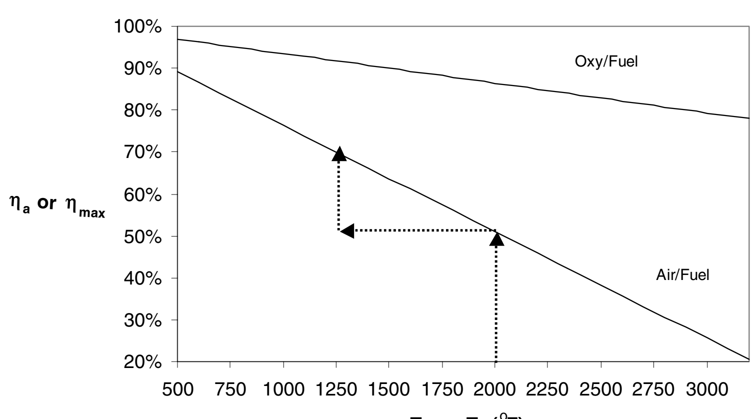
For a given flame temperature, the maximum efficiency occurs when the temperature of the exhaust gases exiting the furnace (T_{ex}) is minimized. T_{ex} must always be above the process temperature (T_p), but it can be reduced to as close to T_p as desired by increasing the size of the furnace and the processing time. In the limit of an infinitely large furnace, the exhaust-gas temperature will equal the process temperature, and the maximum efficiency thus obtained is

$$\eta_{\max} = 1 - \frac{(T_P - T_a)}{(T_{\mathrm{af}} - T_{a)}} \tag{10}$$

Equation (9), η_a, is the best efficiency that can be obtained for an existing real furnace and is nearly achievable. It is just a matter of eliminating wall losses, air infiltration, etc. Equation (10), $\eta_{\max}$, is not achievable because it requires an imaginary infinite furnace. However, it is approachable in that the furnace can be made as large as required to approach as close to $\eta_{\max}$ as desired.

Figure 2 shows these efficiencies plotted vs temperature for an air/fuel and oxygen/fuel furnace. Oxygen enrichment, which is a combination of air and pure oxygen, would fall between the two curves. With the flame temperature fixed, as the exhaust-gas temperature is reduced, the thermal efficiency increases.

An example is shown for a furnace melting scrap aluminum with an exhaust-gas temperature of 2000°F and a process temperature of 1250°F. The best efficiency from all such furnaces, η_a, is 51%. If the exhaust-gas temperature is reduced, the efficiency increases. In the limit of reducing the temperature to that of the process temperature, the furnace would have a maximum efficiency $\eta_{\max}$ of 70%.



hv =	21495 Btu/lbm
AF =	17.195
OF =	4.049
E =	0%
Ta =	70 °F
Cpex =	0.28 Btu/lbm °F
Cpaf =	0.3 Btu/lbm °F

Fig. 2 Thermal efficiency vs temperature for η_a [Eq. (9)] when the exhaust-gas temperature is used and for $\eta_{\max}$ [Eq. (10)] when the process temperature is used.

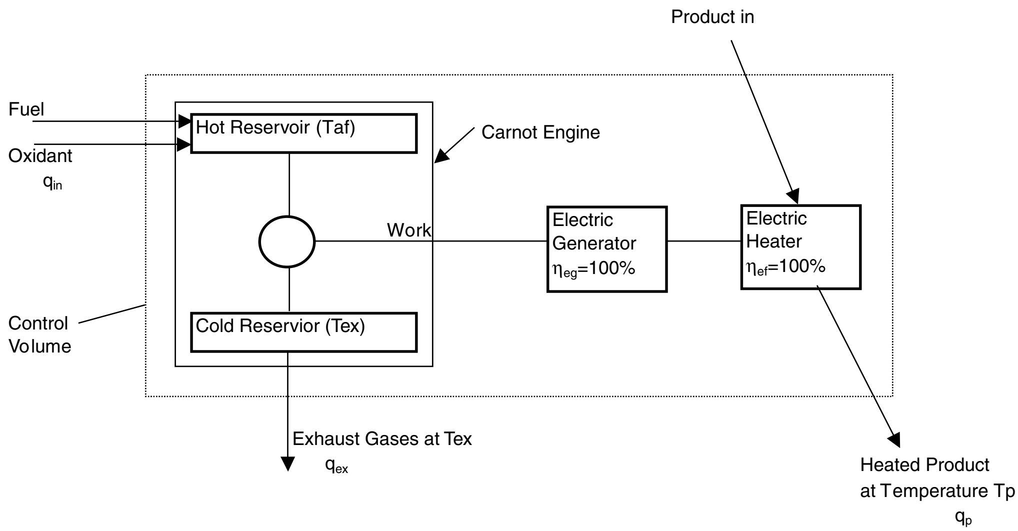


Fig. 3 Process schematic of the Carnot heat engine driving a generator to heat the product.

Carnot Analysis

There is another way to derive Eq. (9). The purpose of a furnace is to transfer heat to a product, but the heat can equally be used to first drive a heat engine, as shown in Fig. 3. The work from the engine can then be used to power an electric generator to electrically heat the product.

The process efficiency is the product of each component efficiency:

$$\eta = \eta_c \eta_{\text{eg}} \eta_{\text{ef}} \tag{11}$$

In practice, an electric generator or electric furnace can have efficiencies over 90%. Hence, taking them to be unity, the furnace efficiency [Eq. (11)] becomes the classical Carnot efficiency:

$$\eta = \eta_c = 1 - \frac{T_{\text{ex}}}{T_{\text{af}}} \tag{12}$$

The two processes depicted in Figs. 1 and 3 are equivalent because all quantities crossing the control volume of each process are the same.[†] Thus, results from one analysis must be true for the other. The difference between Eqs. (9) and (12) is the reference state chosen for each. Ambient conditions are used for η_a (which will be referred to as the ambient efficiency) and absolute zero temperature is used for η_c. The difference in the two references is the energy stored in materials from ambient down to 0°R.

The ambient efficiency η_a is a better choice to use than the Carnot efficiency, because the below-ambient-temperature energy is not available without expending work. To illustrate the difference, if the exhaust temperature of a furnace is reduced to ambient temperature (say, through a recuperator to preheat the air), then the energy released from the fuel would go into the product without losses. Equation (9) mirrors this because it produces an efficiency of 100%. The Carnot efficiency under these circumstances is less than unity.

A comparison of the Carnot and ambient efficiencies is shown in Fig. 4. The efficiencies are similar but diverge as the temperature approaches ambient temperature.

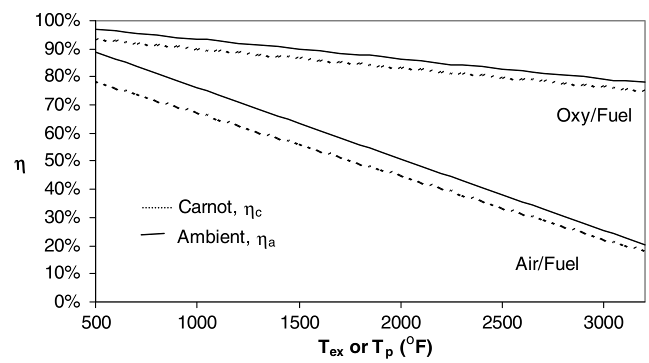


Fig. 4 Efficiency comparison.

Preheated Air Furnaces

The constraint that the exhaust-gas temperature must be above the product temperature does not apply outside the furnace, for which a recuperator can be used to recover the exhaust-gas energy by preheating the combustion oxidant (or preheating the product). With a large enough recuperator, the exhaust-gas temperature can be reduced to any desired temperature approaching ambient temperature, and the thermal efficiency will increase accordingly.

Figure 5 shows the effect for a process with a 2000°F exhaust-gas temperature exiting the furnace. The ambient efficiency increases for both the air and oxygen/fuel systems, though at a quicker rate for the air system. Both curves tend toward 100% as the exiting exhaust-gas temperature tends to the ambient temperature.

Preheating air is difficult and preheating oxygen is daunting. Oxygen's reactivity, strong to begin with, increases exponentially with temperature, making recuperator material compatibility problems a significant hurdle. Additionally, because the thermal efficiency of oxygen/fuel furnaces is high, there is little gain to preheating. For either air or oxygen, metal stress rupture life is greatly diminished ([2], for instance) and metal corrosion is accelerated ([3], for instance) at elevated temperatures.

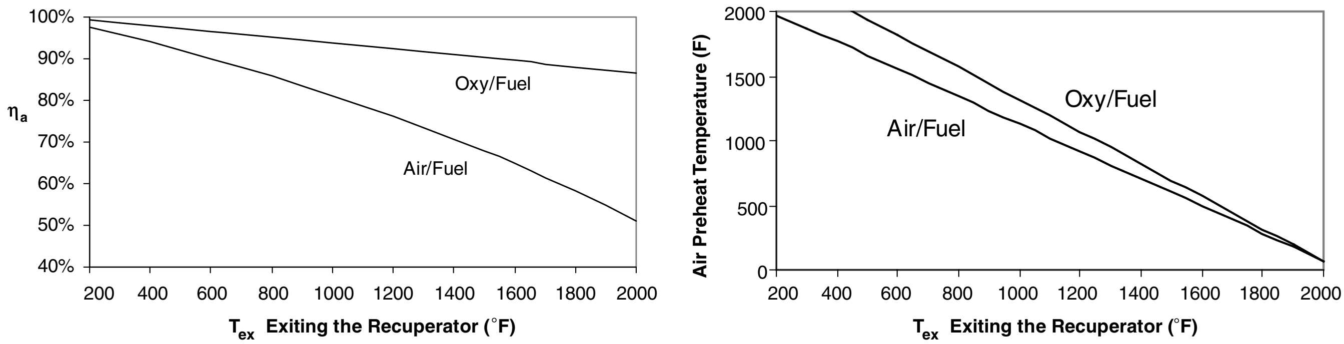
For these reasons, oxygen is never preheated and most air-based recuperators, particularly metal ones, are limited to a preheat temperature of about 1000°F. Figure 6 shows that 1000°F preheating can provide significant efficiency gains with air/fuel systems and only marginal gains with oxygen.

Efficiency of Oxygen/Fuel Furnaces

Oxygen/fuel furnaces require energy to separate the oxygen from the air, which is also affected by the electric power plant's efficiency. Figures 2 and 4–6 ignore this, but if it is desired to know the true energy use, then the analysis must include the separation energy. The modified furnace efficiency then becomes

$$\eta'_{\text{oxy}} = \eta_{\text{oxy}} \frac{h_v}{[h_v + \text{OF}(h_{\text{oxy}}/\eta_{\text{PP}})(1+E)]} \tag{13}$$

[†]The work equals q_p because the electric generator and heater have no losses.



a) b)

Fig. 5 Recuperator effect: a) thermal efficiency and b) preheat temperature.

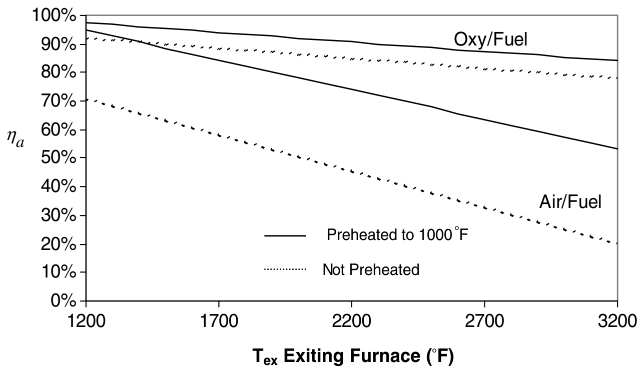


Fig. 6 Efficiency improvements from preheating.

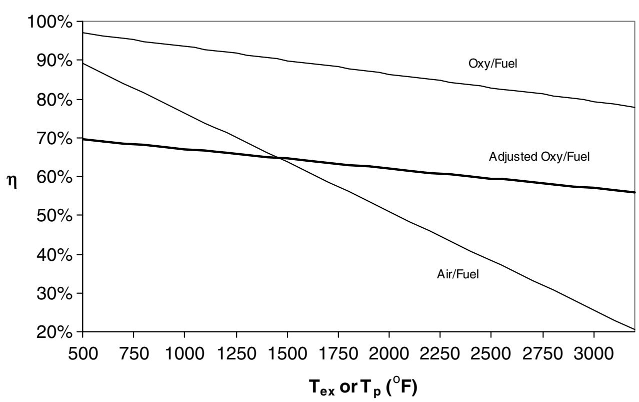


Fig. 7 Thermal efficiency, including the energy to produce the oxygen.

Using 404 kWh/ton for h_{oxy} [4] and 33% for η_{pp}, Fig. 2 is replotted in Fig. 7 with the oxygen/fuel curve shown adjusted for the energy needed to produce the oxygen. For the example in this figure, it would be best to use oxygen/fuel combustion on high-temperature processes with an exhaust-gas temperature over 1450°F. Below that value, there is a net loss in efficiency due to the energy used in producing the oxygen.

There are other reasons to use oxygen/fuel burners, such as reduced emissions, reduced equipment size, and increased production. Also, oxygen enrichment (oxygen and air mixed) would have an energy break-even point at higher temperatures than for oxygen/fuel firing.

Available Energy

There is another way of interpreting the efficiency figures. Available energy (or heat) is defined as the amount of heat released from the combustion process minus the flue gas losses [5]. It represents the energy available to heat the product and make up the other losses, such as wall losses and radiation losses. On the efficiency figures, the space above the curves represents the percent of flue gas losses and the space below the curves represents the percent of available energy. Points on the curve represent the available energy with no other losses and are the best efficiencies possible.

These figures, if thought of as available energy, are useful in calculating the energy change due to a change in a component of the heating system.[‡] For instance, the furnace total firing rate required is simply h_p (the product enthalpy) divided by the available energy. As an example, returning to the aluminum example shown in Fig. 2, with h_p of 511 Btu/lbm at T_{ex} of 2000°F, the available energy with no losses is 51% (air/fuel firing), and therefore the minimum furnace firing rate required is 1002 Btu/lbm. If, however, the measured furnace efficiency falls below the line (say, at 33%), then the furnace firing rate would be 1533 Btu/lbm. As another example, if additional insulation were added to a 33%-efficient furnace and the wall loses were reduced by 100 Btu/lbm, the firing rate would be reduced by 300 Btu/lbm.

Minimum Specific Energy and U.S. Department of Energy's Bandwidth Analysis

The previous development was for an ideal furnace with no losses other than flue gas losses. In this section, a furnace with real losses (included in the term q_w) is analyzed to show how such a furnace can be made to approach an ideal case by developing expressions for the furnace specific-energy consumption.

Specific energy (or energy intensity) is defined as the total energy input divided by the throughput:

$$\mathrm{SE} = \frac{q_{\mathrm{in}}}{\dot{m}_p} \tag{14}$$

An expression for SE can be derived by substituting Eqs. (4) and (6–8) into Eq. (2) and dividing by $\dot{m}_p$:

$$\mathrm{SE} = \frac{q_w}{\dot{m}_p \eta_a} + \frac{h_p}{\eta_a} \tag{15}$$

where η_a from Eq. (8) is used as a definition to simplify the form of Eq. (15).

For a given product, h_p is fixed and the minimum specific energy occurs when the first term on the right side of the equation is much smaller than the second term, which can occur at high throughputs, so that the minimum SE becomes

$$\mathrm{S\,E}_{\min} = \frac{h_p}{\eta_a} \tag{16}$$

[‡]Personal communication with Arvind Thekdi of E3M, Inc., May 2007.

For this to occur,

$$\frac{q_w}{\dot{m}_{\max}} \ll h_p \tag{17}$$

or

$$\alpha = \frac{q_w}{h_p \dot{m}_{\max}} \ll 1 \tag{18}$$

Equation (16) shows the minimum specific energy possible for a furnace and Eq. (18) shows the required condition to achieve it.

Equation (15) can be nondimensionalized by using Eqs. (16) and (18):

$$\frac{\mathrm{SE}}{\mathrm{SE}_{\min}} = \alpha\left(\frac{\dot{m}_{\max}}{\dot{m}_p}\right) + 1 \tag{19}$$

Two examples are given in Figs. 8 and 9. The first is for a rotating kiln used to remove organics from scrap aluminum [6]. Combustion gases from a burner flow into the kiln after being diluted to 1500°F. The second is for a stack melter used to melt aluminum ingots [7]. The ingots are placed in the stack, in which the bottom ones melt and pass to a holding chamber and the top ones are preheated by the escaping exhaust gases. In both figures, the measured specific energy is plotted along with Eq. (19), with α chosen to match the data.

The kiln is not considered to be energy-efficient because α is 3.1, which is not surprising, due to the reported air leakage. The stack melter is an energy-efficient process ($\alpha = 0.25$), due in part to the ingot preheating.

The Department of Energy's Industrial Technology Program is conducting a bandwidth analysis of the top energy-consuming industrial sectors to determine how much energy is used and how much can be saved. The pulp and paper and chemical industry bandwidth studies have been completed [8,9] and others are in progress. Equation (16) shows the minimum specific energy that should be applied to this bandwidth study. As an example, the secondary aluminum melter from Fig. 2 has an η_a of 51%. With an h_p of 511 Btu/lbm taken from [10], the $\mathrm{SE}_{\min}$ is 1002 Btu/lbm. For the given furnace and for similar furnaces, it is not possible to reduce the specific energy below this value. This then provides a measure of how well such furnaces can be operated.

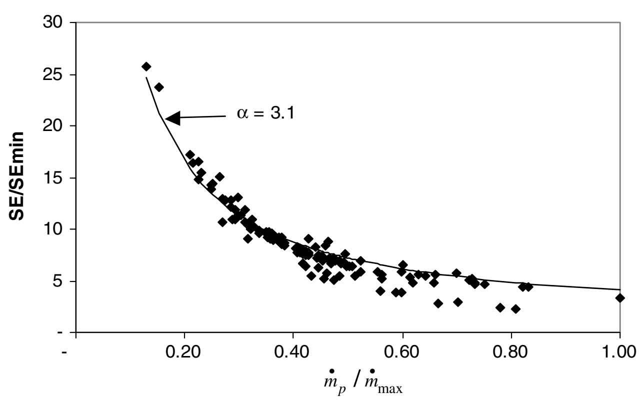


Fig. 8 Rotating kiln performance.

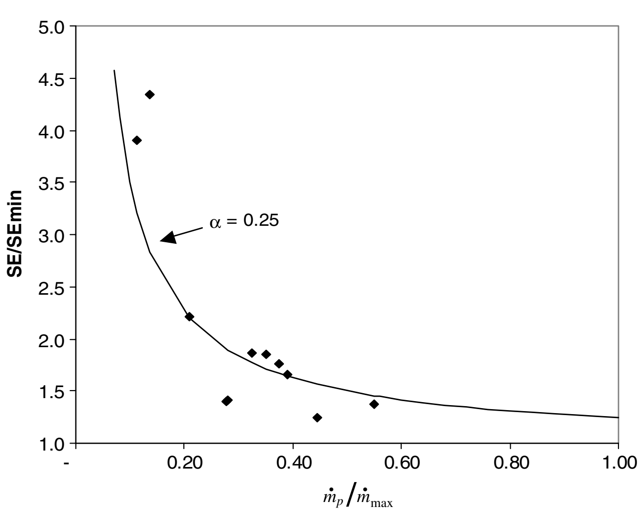


Fig. 9 Stack melter performance.

Problem with Reversible Efficiencies

The efficiencies that lack the specific heat terms, Eq. (9) or Eq. (12), are based on a reversible process and therefore should be the maximum efficiencies possible. This, however, is not the case. Equation (8), which includes the specific heats, yields an efficiency higher than Eq. (9) because the specific heat in the denominator, C_{paf}, is larger than that in the numerator, C_{pex}. It is not clear why an efficiency based on a reversible process would have a lower efficiency than one without such a constraint.

Conclusions

The limiting thermal efficiency for furnaces was derived and it was shown to be the same as the classical Carnot efficiency for heat engines. The analysis is robust and simple and can be applied to any device transferring heat to a load, such as furnaces, boilers, lehrs, kilns, and ovens.

Further, it is more practical to use an ambient temperature reference, rather than the absolute reference used in the Carnot analysis, because furnaces can only use the heat that is above ambient temperature.

Thermal efficiencies improve with decreasing exhaust-gas temperature because more of the energy in the gas is used. The maximum efficiency achievable, therefore, is when the exhaust-gas temperature approaches the product temperature.

Expressions were developed that show the minimum specific energy achievable by a furnace and the condition in which this can occur. This was compared with two processes using measured specific-energy data. Other results are as follows:

1) In furnaces with waste heat recovery to preheat the combustion air, efficiencies approaching 100% are possible (if the exhaust-gas temperature is reduced to the ambient temperature). However, practical considerations limit the air preheat temperature to 1000°F and oxygen, due to its high reactivity, should not be preheated.

2) In oxygen/fuel-fired furnaces, the energy expended producing the oxygen should be included in the analysis. For the example given, oxygen/fuel firing should be used with high-temperature processes, with exhaust-gas temperatures above 1450°F.

3) The U.S. Department of Energy's bandwidth analysis demonstrated the theoretical limit in specific energy that exists for industrial processes.

4) A problem was identified: the furnace reversible efficiencies are lower than the irreversible efficiencies.

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