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Energy Efficient Process Heating: Managing Air Flow

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ABSTRACT

Much energy is lost through excess air flow in and out of process heating equipment. Energy saving opportunities from managing air flow include minimizing combustion air, preheating combustion air, minimizing ventilation air, and reconfiguring openings to reduce leakage. This paper identifies these opportunities and presents methods to quantify potential energy savings from implementing these energy-savings measures. Case study examples are used to demonstrate the methods and the potential energy savings.

The method for calculating savings from minimizing combustion air accounts for improvement in efficiency from increased combustion temperature and decreased combustion gas mass flow rate. The method for calculating savings from preheating inlet combustion air consists of fundamental heat exchanger and combustion efficiency equations. This method accounts for the reduction of combustion air flow as fuel input declines, which is often neglected in many commonly-used methods. The method for calculating savings from reducing forced ventilation in ovens accounts for flow rate of ventilation air and air temperature when entering and exhausting the oven. The method for calculating savings from reconfiguring oven openings accounts for flow rate of air entering and exiting the oven due to buoyancy forces.

INTRODUCTION

Managing air flow is usually the most important aspect to consider when attempting to improve the energy efficiency of most process heating systems. The largest loss in fuel-fired process heating is nearly always the loss through the exhaust stack, which is often greater than all other losses combined (Thekdi, 2005). For example, in a boiler, about 20% of input energy is lost in the exhaust gasses while only about 2% is lost through the boiler shell. For higher temperature applications, even more energy is lost in the exhaust gasses because they leave the system at higher temperatures. For example, boilers generating steam at 250 F to 350 F typically have efficiencies of about 80%. Furnaces that melt aluminum at 1,400 F have efficiencies of about 50%, and furnaces that melt glass at 2,500 F have efficiencies of about 30%.

Although most or all air in a fuel-fired heating system leaves the system through the exhaust stack, air enters the system as combustion air, ventilation air, and infiltration air. Figure 1 shows a process heating system with the major categories of air flow.

Combustion air enters the system through burners. Ventilation air is either pushed through the system by intake ventilation fans or pulled through the system by exhaust fans. Infiltration air enters the system through openings in the system shell. For energy-efficient process heating, the quantity of combustion air should be only slightly higher than stoichiometric minimum needed to combust the fuel, the quantity of ventilation air should be at minimum level necessary to dilute combustibles/moisture to safe/acceptable levels, and infiltration air should be minimized or eliminated. Preheating incoming air streams can also increase efficiency.

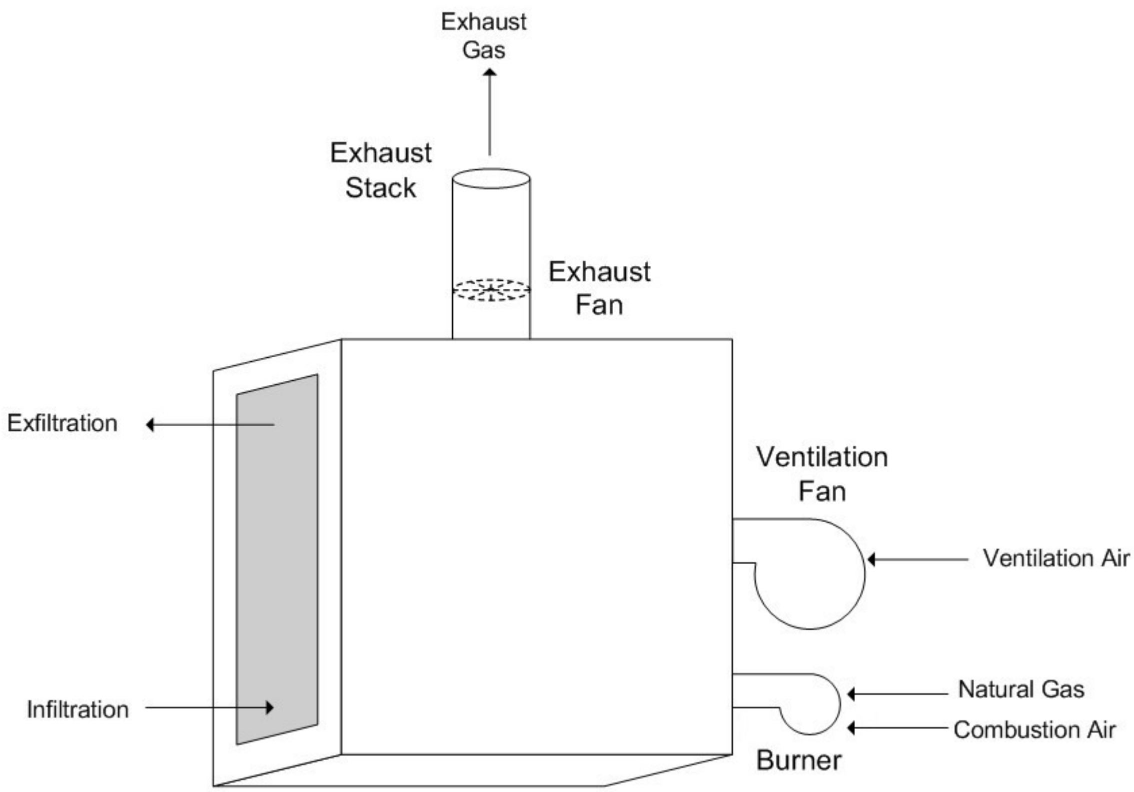


Figure 1. Combustion, ventilation and infiltration air flows in process heating system

This paper discusses opportunities to increase efficiency by managing air flow and presents methods to calculate the resultant energy savings. The paper focuses on fuel-fired heating systems, however, opportunities presented in the Increasing Efficiency by Managing Ventilation Air and Increasing Efficiency by Managing Infiltration sections can be applied to systems whose heat is from another source such as electricity. A companion paper, "Energy Efficiency Process Heating: Insulation and Thermal Mass", discusses improving process heating energy efficiency through insulation and thermal mass.

DETERMINING COMBUSTION EFFICIENCY

The three most common losses in a fuel-fired process heating system are exit gas losses, conduction losses through the shell, and losses due to heating the thermal mass of the system, conveyors, and racking. Combustion efficiency is the percentage of fuel energy supplied that is not lost through exiting gasses, but is absorbed by the system. Energy absorbed by the system is either transferred to the final product, absorbed by the system's thermal mass, or lost through the system shell, and is often referred to as "available heat" (Thekdi, 2005). Overall efficiency is the percentage of fuel energy supplied that is transferred to the final product, and is always less than combustion efficiency.

Methods for calculating combustion efficiency for systems with only combustion air and for systems with combustion air plus either ventilation and/or infiltration air are derived below. The methods use easily measured input variables.

Combustion Efficiency for Systems With Only Combustion Air

The minimum amount of air required for complete combustion is called the "stoichiometric" air. Assuming that natural gas is made up of 100% methane, the equation for the stoichiometric combustion of natural gas with atmospheric air is:

$$CH_4 + 2\ (O_2 + 3.76\ N_2) \rightarrow CO_2 + 2\ H_2O + 7.52\ N_2 \qquad (1)$$

The ratio of the mass of air required to completely combust a given mass of fuel is called the stoichiometric air to fuel ratio, AFs. For natural gas, AFs is about 17.2 lb-air/lb-ng. The quantity of air supplied in excess of stoichiometric air is called excess combustion air, ECA. Excess combustion air can be written in terms of the stoichiometric air to fuel ratio, AFs, the combustion air mass flow rate, m_{ca}, and natural gas mass flow rate, m_{ng}.

$$ECA = [(m_{ca} / m_{ng}) / AFs] - 1 \qquad (2)$$

Large quantities of excess air dilute combustion gasses and lower the temperature of the gasses, which results in decreased efficiency.

The energy input, Q_{in}, to a combustion chamber is the product of the natural gas mass flow rate, m_{ng}, and the higher heating value of natural gas, HHV, which is about 23,900 Btu/lbm.

$$Q_{in} = m_{ng} \cdot HHV \qquad (3)$$

The mass flow rate of the combustion gasses, m_g, is the sum of the natural gas mass flow rate, m_{ng}, and combustion air mass flow rate, m_{ca}.

$$m_g = m_{ng} + m_{ca} \qquad (4)$$

The temperature of combustion, T_c, can be calculated from an energy balance on the combustion chamber (Figure 2), where the chemical energy released during combustion is converted into sensible energy gain of the gasses.

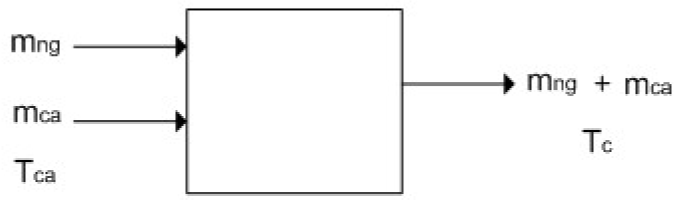


Figure 2. Mass balance on combustion chamber

The energy balance reduces to the terms of inlet combustion air temperature, T_{ca}, lower heating value of natural gas (about 21,500 Btu/lbm), excess combustion air, ECA, stoichiometric air fuel ratio, AFs, and specific heat of combustion gasses, Cp_g (about 0.26 Btu/lbm-F) (Carpenter and Kissock, 2005). Equation 5 calculates combustion temperature, T_c, in terms of these easily measured values.

$$T_c = T_{ca} + LHV / [\{1 + (1 + ECA)\ AFs\} \cdot Cp_g] \quad (5)$$

The efficiency of a process heating system, η, is the ratio of energy absorbed by the system to the total fuel energy supplied. The energy absorbed by the system is the energy loss of combustion gasses as it travels through the system; which on a per unit basis can be written in terms of excess combustion air, ECA, stoichiometric air/fuel ratio, AFs, specific heat of combustion gasses, Cp_g, combustion temperature, T_c, and exhaust gas temperature, T_{ex}. The total fuel energy supplied, on a per unit basis, is the higher heating value of natural gas, HHV. Equation 6 calculates combustion efficiency, η, in terms of easily measured values.

$$\eta = [\{1 + (1 + ECA) \cdot AFs\} \cdot Cp_g \cdot (T_c - T_{ex})] / HHV \quad (6)$$

Exhaust gas temperature, T_{ex}, and excess combustion air, ECA, can be measured using a combustion analyzer. The useful heat output, Q_{out}, in a process heating system is the heat input to the burner, Q_{in}, multiplied by the efficiency, η.

$$Q_{out} = Q_{in} \cdot \eta \quad (7)$$

Combustion Efficiency for Systems With Ventilation/Infiltration Air

Ventilation or infiltration air has the same effect on efficiency as excess combustion air; it dilutes and cools combustion gasses. Adding terms for the mass flow rate of ventilation air, m_{ven} and mass flow rate of infiltration air, m_{inf}, to Equation 4, the mass flow rate of gasses, m_g, is:

$$m_g = m_{ng} + m_{ca} + m_{ven} + m_{inf} \quad (8)$$

The mass flow rate of gasses, m_g, is also the sum of mass flow rate of exhaust gas, m_{ex}, and exfiltration out of the system, m_{exfil}.

$$m_g = m_{ex} + m_{lexfil} \quad (9)$$

Rearranging Equation 2 and substituting in m_g from Equation 8, total excess air, EA, can be written as:

$$EA = [(m_g / m_{ng} - 1) / AFs] - 1 \qquad (10)$$

Effective combustion temperature, $T_{c,eff}$, is defined as the combustion temperature if all air (combustion and infiltration) entered the process heat system through the combustion chamber. This term is lower than actual combustion temperature, T_c, inside the burner because it takes into account the dilution and cooling of combustion gasses when ventilation and/or infiltration air is present. Effective combustion temperature incorporates total excess air and takes into account the dilution and cooling of combustion gasses from infiltration air.

Equation 11 calculates effective combustion temperature, $T_{c,eff}$, by replacing T_c with $T_{c,eff}$ and ECA with EA in Equation 5, and adding the terms of ventilation air temperature, T_{ven}, and infiltration air temperature, T_{inf}. The terms f_{ca}, f_{ven}, and f_{inf} are also added, which represent the fraction of total air entering the system attributed to combustion air, ventilation air, and infiltration air, respectively.

$$T_{c,eff} = T_{ca} \cdot f_{ca} + T_{ven} \cdot f_{ven} + T_{inf} \cdot f_{inf} + LHV / [\{1 + (1 + EA)\ AFs\} \cdot Cp_g] \qquad (11)$$

In most cases, the temperatures of incoming combustion, ventilation air, and infiltration air equal the temperature of ambient air, T_a. Thus, Equation 11 can be simplified to:

$$T_{c,eff} = T_a + LHV / [\{1 + (1 + EA)\ AFs\} \cdot Cp_g] \qquad (12)$$

EA and $T_{c,eff}$ can be substituted into Equation 6 to find combustion efficiency for a system where ventilation and/or infiltration is present.

$$\eta = [\{1 + (1 + EA) \cdot AFs\} \cdot Cp_g \cdot (T_{c,eff} - T_{ex})] / HHV \qquad (13)$$

The equations are easily incorporated into spreadsheets or computer programs such as PHAST (US DOE, 2004) and HeatSim (Kissock and Carpenter, 2001).

INCREASING EFFICIENCY BY MANAGING COMBUSTION AIR

Minimizing Combustion Air

The optimal quantity of excess combustion air to guarantee complete combustion in most natural gas burners is about 10% (EPA, 2001). This produces combustion gasses with about 1.7% O_2 content when combusting natural gas. However, many process heating systems operate with much larger levels of excess air. Minimizing excess combustion air to about 10%, increases combustion efficiency and reduces gas use.

Method For Estimating Savings

To calculate energy savings from reducing excess combustion air to 10%, Equations 5 and 6 can be used to calculate system efficiency, η, with current excess air quantity, and new efficiency, η_n, if excess air were reduced to 10%. Exhaust temperature, T_{ex}, in Equation 6 may change slightly as excess air changes. However, the change is typically small and can be neglected (Carpenter and Kissock, 2005). When an energy-savings measure is implemented to improve combustion efficiency from η to η_n, the useful energy output remains the same, but energy input reduces from Q_{in} to $Q_{in,n}$. Thus,

$$Q_{in} / \eta = Q_{in,n} / \eta_n \tag{14}$$

Energy savings, Q_{sav} is the difference between Q_{in} and $Q_{in,n}$.

$$Q_{sav} = Q_{in} - Q_{in,n} \tag{15}$$

Combining Equation 22 with Equation 23 gives:

$$Q_{sav} = Q_{in} \cdot (1 - \eta / \eta_n) \tag{16}$$

Savings Example

For example, we analyzed the exhaust gasses from a well-sealed melting furnace using a combustion analyzer. The temperature of the exhaust gasses was 1,465 F and the quantity of excess air was 95%. From Equations 5 and 6, the current combustion efficiency of the melt furnace was 39%. The combustion efficiency would increase to 60% if excess air were reduced to 10%. This would result in a 35% savings in energy use.

Preheating Combustion Air

Fuel-fired heating systems frequently use atmospheric air as a combustion oxidizer and have an exhaust stack where spent combustion gasses leave the system. It is often economical to install a gas-to-gas heat exchanger, called a recuperator, to reclaim energy from the exhaust gasses to preheat the inlet combustion air. The recuperator diagram in Figure 3 shows the heat transfer, Q, from exhaust combustion gasses to inlet combustion air. The entering and exiting temperatures are T_{ex1} and T_{ex2}, respectively, for exhaust combustion gasses, and T_{ca1} and T_{ca2}, respectively, for inlet combustion air.

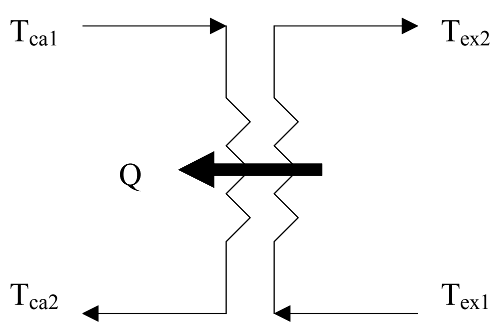


Figure 3. Recuperator schematic

The heat transferred from the exhaust gasses to the combustion air can be calculated using the heat exchanger effectiveness method. Many analyses equate natural gas savings with the heat reclaimed from the exhaust gasses using current temperatures and gas flow rates. We call this method of estimating savings the "heat exchanger method". However, the reclaimed energy reduces the quantity of natural gas required to meet the load, and hence reduces the combustion and exhaust air flow rates. Taking these reduced flow rates into account increases the efficiency of the system and results in greater savings than would have been estimated without taking these effects into consideration. We call this more accurate method of calculating savings from preheating air the "system efficiency improvement method".

Method For Estimating Savings

The effectiveness, ε, of a heat exchanger is defined as the ratio of actual energy transferred, Q, to maximum possible energy transferred. Recuperator effectiveness can typically be found in manufacturers' literature. The maximum possible energy transferred in a recuperator is the product of combustion air mass flow rate, m_{ca}, specific heat of air, Cp_a, and the difference between temperatures of inlet combustion air and spent combustion gasses upon entry to the recuperator, T_{ca1} and T_{ex1}. Thus, the equation for effectiveness, ε, is:

$$\varepsilon = Q / [m_{ca} \cdot Cp_a \cdot (T_{ex1} - T_{ca1})] \quad (17)$$

Exhaust temperature, T_{ex1}, and inlet combustion air temperature, T_{ca1}, are easily measured values. If heat input to the burner, Q_{in}, and excess combustion air, ECA, are known, Equations 3 and 2 can be used to calculate combustion air mass flow rate, m_{ca}. Equation 17 can then be used to calculate energy transferred through the recuperator, Q. The energy savings, Q_{sav}, for this method is the energy transferred, Q.

The energy transferred through a recuperator, Q, is equal to the product of combustion air mass flow rate, m_{ca}, specific heat of air, Cp_a, and the difference between temperature of inlet combustion air upon entry and exit of the recuperator, T_{ca1} and T_{ca2}. Thus,

$$Q = m_{ca} \cdot Cp_a \cdot (T_{ca2} - T_{ca1}) \quad (18)$$

Substituting Equation 18 into Equation 17, effectiveness, ε, can be written as:

$$\varepsilon = (T_{ca2} - T_{ca1}) / (T_{ex1} - T_{ca1}) \quad (19)$$

Equation 19 can be used to calculate temperature of inlet combustion air upon exit of the recuperator, T_{ca2}. Assuming no infiltration occurs in the process heating system, Equation 5 can be used to calculate combustion temperature before and after recuperator installation, T_{c1} and T_{c2}, by substituting T_{ca1} and T_{ca2} for T_{ca}. Subsequently, Equation 6 can be used to calculate combustion efficiency before and after the retrofit, η and η_n. If heat input to the burner, Q_{in}, is known, Equation 16 can be used to calculate energy savings, Q_{sav}.

Savings Example

We analyzed an aluminum melting furnace that had been retrofit with a 38% effective recuperator. The furnace had operated at 0.5 mmBtu/hr input before the retrofit. The exhaust gas temperature from the furnace was 1,465 F, plant air temperature used for combustion was 95 F, and excess combustion air content was 95%. From Equation 3, natural gas mass flow rate was about 21 lbm/hr. From Equation 2, combustion air mass flow rate was about 704 lbm/hr. From Equations 5 and 6, the combustion temperature before the retrofit was about 2,489 F, and combustion efficiency was about 38%.

Using the heat exchanger method, the energy saved by installing the recuperator, from Equation 17, would be about 0.095 mmBtu/hr.

Using the system efficiency improvement method, the temperature of inlet combustion air upon exit from the recuperator, from Equation 19, is about 615 F. From Equations 5 and 6, the new combustion temperature is about 3,009 F. Using these values, the combustion efficiency after the retrofit was 58%. From Equation 16, energy saved is about 0.172 mmBtu/hr. Note that this result shows that the actual energy savings are about 81% greater than predicted by the heat exchanger method.

Using Exhaust Air as Combustion Air

Sometimes curing and drying ovens introduce large quantities of ventilation air into the oven to dilute combustibles or moisture. At high ventilation levels, the O_2 content in the exhaust stream may be 17% or greater, which is close to the 20% oxygen content of ambient air. In these cases, the warm exhaust gasses could be redirected to the burner and used as combustion air.

Method For Estimating Savings

Equation 11 can be used to calculate effective combustion temperature when warm exhaust air is used for combustion by substituting exhaust temperature, T_{ex}, for T_{ca}. Equation 13 can be used to calculate combustion efficiency before and after the system modification, and Equation 16 can be used to calculate energy savings, Q_{sav}.

Savings Example

For example, consider a curing oven that adds 70 F ventilation air to dilute combustibles. The temperature of the diluted exhaust gasses is 250 F and an O_2 content of the exhaust gasses is 18% (about 661% excess air). Combustion air accounts for 20% of the total air entering the system. From Equations 12 and 13, the effective combustion temperature is about 697 F and combustion efficiency is about 64%. If some of the exhaust air were used as combustion air, the effective combustion temperature would increase to about 715 F, and combustion efficiency would increase to about 67%. This would reduce total oven energy use by about 4%.

INCREASING EFFICIENCY BY MANAGING VENTILATION AIR

Curing ovens, which evaporate paint or volatile organic compounds, require enough ventilation to maintain the oven atmosphere at safe levels to prevent a fire hazard. In these ovens, extra air can be induced into the oven by exhaust air fans or forced into the oven by supply air fans.

Finding Required Ventilation Air for a Curing Process

According to National Fire Protection Agency (NFPA) Standard 86, industrial oven atmospheres must never exceed 25% of the lower explosive limit (LEL). When curing paint, about 10,000 standard cubic feet of fresh ventilation air are required per gallon of paint cured to maintain 25% LEL (IDEM, 2001). If an oven has a constant volume ventilation fan, the flow rate must be designed to meet conditions of maximum production when the greatest amount of substance passes through the oven.

At standard temperature and pressure, air has a density of 0.074 lbm/ft^3. Thus, about 740 lbm of ventilation air is required per gallon of cured paint. If the maximum hourly volume of paint, V_p, is known in a curing process, the required mass flow rate of ventilation air, $m_{ven,req}$, can be calculated using Equation 20.

$$m_{ven,req} \text{ (lbm/hr)} = V_p \text{ (gal/hr)} \cdot 740 \text{ lbm-air/gal-paint} \quad (20)$$

Minimizing Ventilation Air

Ventilation levels in ovens are typically much higher than needed to maintain 25% LEL. If so, the ventilation rates can be reduced by changing the fan sheave or closing dampers as an energy saving measure.

Method For Estimating Savings

Energy savings from reducing ventilation to the minimum required can be calculated if excess air, EA, mass flow rate of gasses through the system, m_g, and maximum hourly volume of paint in the curing process, V_p, are known. The quantity of excess air can be measured using a combustion analyzer in the exhaust stack. Mass flow rate of gasses through the system can be found by measuring exhaust velocity with an anemometer using ventilation fan specifications. The density of gasses will be very close to the density of air at internal oven temperature and atmospheric pressure, and can be calculated using the ideal gas equation. If gas leaks out of the system in places other than through the exhaust stacks, the flow rate, m_{leak}, should be measured or estimated and added to exhaust flow rate, m_{ex}, to find m_g.

$$m_g = m_{ex} + m_{leak} \quad (9)$$

Once m_g is known, the natural gas mass flow rate, m_{ng}, can be calculated using Equation 10. Subsequently, heat input to the system, Q_{in}, can be calculated using Equation 3. If excess combustion air, ECA, is known, Equation 2 can be used to calculate mass flow rate of combustion air, m_{ca}. If excess combustion air is not known, it can be estimated to be between 10% and 50%. Mass flow rate of infiltration, m_{inf}, is equal to mass flow rate of gas leaking out of the system. The next section discusses infiltration in greater detail.

With natural gas mass flow rate, m_{ng}, combustion air mass flow rate, m_{ca}, and infiltration mass flow rate, m_{inf}, known, Equation 8 can be used to calculate ventilation mass flow rate, m_{ven}. To calculate the new mass flow rate of gasses, $m_{g,n}$, through the system when ventilation is reduced to minimum safe levels, $m_{ven,req}$ can be substituted for m_{ven} in Equation 8. Equation 10 can then be used to calculate new excess air, EA_n, by substituting $m_{g,n}$ for m_g. Equations 12 and 13 can be used to calculate the current combustion efficiency, η, and new combustion efficiency, η_n, using values for current excess air, EA, and new excess air, EA_n. Exhaust temperature, T_{ex}, in this case, is the internal oven temperature. Equation 16 can then be used to calculate energy savings, Q_{sav}.

For greater energy efficiency, LEL monitors can be purchased and installed to control ventilation to maintain a certain LEL. Otherwise, ventilation levels must be enough to support maximum operating conditions in a curing process.

The above methodology can be used to find the energy savings from reducing oven exhaust to its minimum safe level. Some curing processes, however, require ventilation to be higher than the minimum safe level for enhancement of final paint color or for other reasons. When reducing ventilation in an oven, caution should be taken to assure that the final product is not adversely affected.

Savings Example

We analyzed the exhaust gasses of an ink cure oven, and found the temperature to be 141 F with 3,700% excess air, which results in a combustion efficiency of 43%. The mass flow rate of gasses through the system was 16,000 lb/hr, and 15,600 lb/hr was attributed to ventilation air. The internal set-point temperature of the oven was 300 F, but oven ventilation was so high that ventilation air diluted the exhaust to a temperature of 141 F. The volume of ink through the oven was 0.26 gal/hr, which requires 195 lb/hr of ventilation air to maintain levels beneath 25% LEL. If ventilation air were reduced to 195 lb/hr, excess air would reduce to 75%. Assuming exhaust temperature would increase to the set-point temperature of 300 F, combustion efficiency would increase to 82%, and a 47% savings in energy use would result.

Using Thermal Oxidizer Air as Ventilation Air

Energy savings can also be achieved by reusing discharge air from a thermal oxidizer as ventilation air. This is possible because thermal oxidizers burn off virtually all of the volatile organic compounds. Discharge temperatures from thermal oxidizers depend on the numer of stages and effectiveness of heat recovery, but are almost always 300 F or higher.

Method For Estimating Savings

The temperature of discharge air from the thermal oxidizer can be plugged into the T_{inf} term of Equation 11 to find effective combustion temperature, $T_{c,eff}$. Equation 13 can then be used to calculate combustion efficiency, η, after reusing thermal oxidizer discharge air, and Equation 16 can be used to calculate energy savings, Q_{sav}.

Savings Example

For example, consider a curing oven operating at 400 F that adds 70 F ventilation air to dilute combustibles. The quantity of excess air in the exhaust gasses is 100%, and ventilation air accounts for 40% of the total air entering the system. The exhaust gasses are directed to a thermal oxidizer that discharges the gasses at 500 F. From Equations 12 and 13, the effective combustion temperature is about 2,406 F and combustion efficiency is about 77%. If some of the discharge air from the thermal oxidizer were recirculated as ventilation air, the effective combustion temperature would increase to about 2,578 F, and combustion efficiency would increase to about 84%. This would reduce total oven energy use by about 8%.

IMPROVING EFFICIENCY BY MANAGING INFILTRATION

The air pressure inside ovens and furnaces is typically slightly less than the atmospheric pressure surrounding the oven. Thus, if the shell is not tightly constructed, cool ambient air is drawn into the oven/furnace, and is heated to the operating temperature of the oven/furnace. Heating the infiltrating air requires excess energy. Examples of sources of infiltration air leaks are unsealed doorways, cracks in firebricks, and loose joints.

Infiltration is always present in continuous curing or dryoff ovens with open doorways for parts to enter and exit. Parts or product being cured or dried in continuous process ovens are commonly transported through the oven via a monorail or conveyor, as shown in Figure 4. In an oven with vertical openings, warm air rises to the oven's ceiling due to buoyancy forces and exfiltrates out of the top of vertical openings. An equal amount of cool ambient air infiltrates into the oven through the bottom half of the vertical openings. Figure 4 shows a typical velocity profile of infiltration and exfiltration air through a vertical oven opening. The velocities are greatest at the top and bottom of the openings. A balance point occurs near the center of the opening where air leaks neither into nor out of the oven. The velocity of infiltration and exfiltration can be measured with by performing a traverse from the top of the opening to the bottom of the opening with an anemometer.

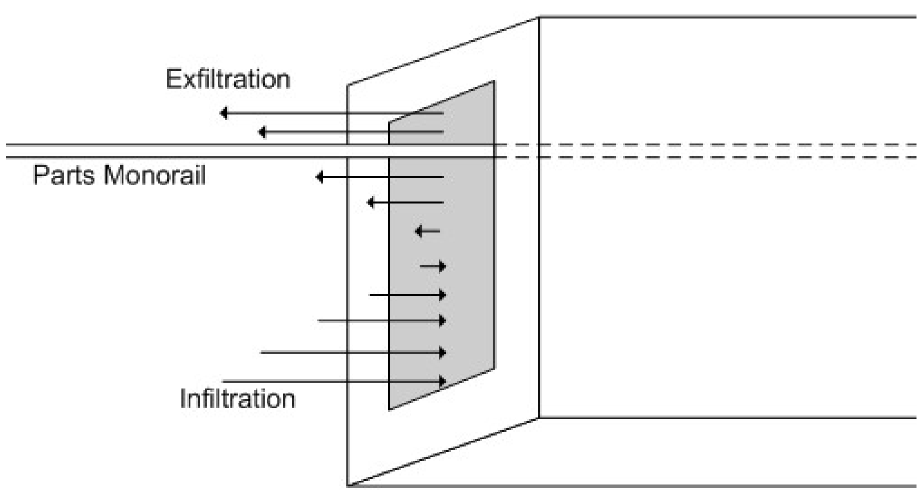


Figure 4. Air velocity profile through vertical oven opening

Improving Efficiency by Moving Opening to Oven Floor

For elevated ovens, it may be possible to move the opening from a vertical wall to the floor of the oven, as shown in Figure 5. Doing so almost entirely eliminates infiltration due to buoyancy effects.

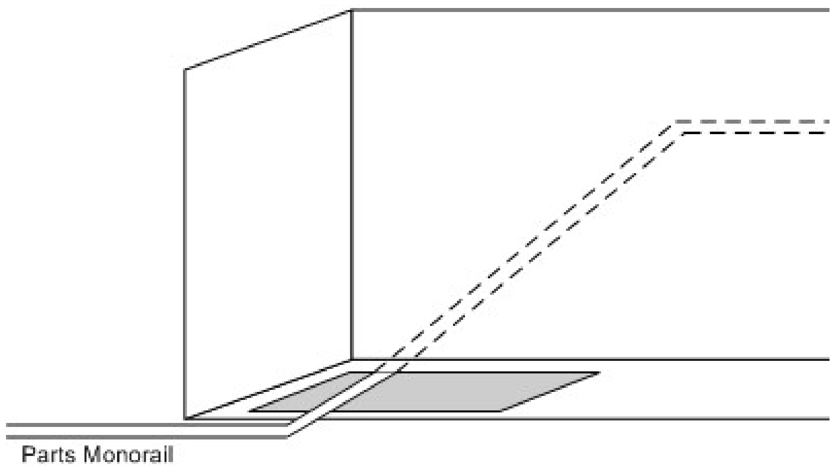


Figure 5. Oven with parts entering through floor

Method For Estimating Savings

The infiltration energy lost, Q_{inf}, from vertical openings can be calculated as the product of average velocity of exfiltration air, V_{exfil}, the area over which air leaks outward, A, density of air, ρ_a, specific heat of air, Cp_a (about 0.24 Btu/lbm-F), and the difference between temperature of exfiltration air, T_{exfil}, and infiltration air, T_{inf}.

$$Q_{inf} = V_{exfil} \cdot A \cdot \rho_a \cdot Cp_a \cdot (T_{exfil} - T_{inf}) \quad (21)$$

For vertical openings, the area over which air exfiltrates is about half the area of the opening. In horizontal openings, as shown in Figure 5, warm air remains at the top of the oven and cool ambient air stays below the vertical opening. Thus, infiltration falls to virtually zero. To be conservative, one could assume that 80% of energy lost from infiltration would be eliminated. Energy saved, Q_{sav}, would be calculated with Equations 21 and 22.

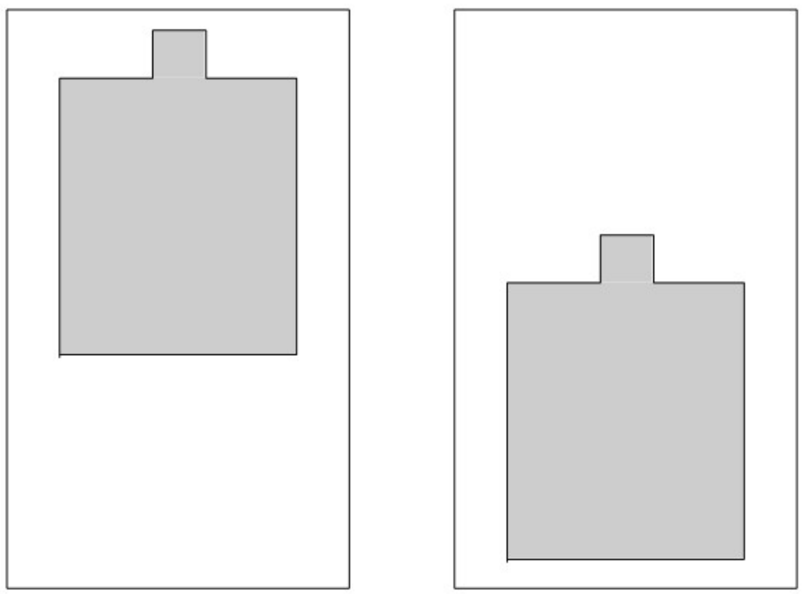
$$Q_{sav} = Q_{inf} \cdot 80\% \quad (22)$$

Savings Example

We analyzed a cure oven located on the second story of a plant, with vertical entrance and exit areas measuring about 100 ft^2. We measured the average exfiltration velocity to be 100 ft/min over a 50 ft^2 area, and the internal oven temperature was 435 F. If the oven were retrofit so that the entrances and exits were oriented horizontally through the floor, total oven energy use would be reduced by about 40%.

Improving Efficiency by Lowering Openings

The quantity of infiltration air through a vertical opening is a function of the height of the opening and the temperature difference between the oven air at the opening and the ambient plant air. In many ovens, vertical openings are near the top of ovens and have room to be moved lower. If the openings were moved lower, infiltration would reduce because the temperature difference between ambient plant air and oven air at the opening would be smaller. Moving the opening usually requires moving the monorail or conveyor; however, the energy savings may be sufficient to fund the project. Figure 6 shows the position of a monorail opening located near the top of the oven and the new position after an energy-savings retrofit.



(a) (b)

Figure 6. Oven face with high vertical opening (a) and more energy-efficient low vertical opening (b).

<u>Method For Estimating Savings</u>

The net pressure difference, P_{net}, between the bottom and the top of the column is a function of column height, h, temperature inside the column, T_i, and temperature outside the column, T_o (Equation 23; Seryak and Kissock, 2002; Jones and West, 2001). The constants in the equation are the acceleration due to gravity, g (32.2 ft/s^2), atmospheric pressure, P_{atm} (14.7 psi), and the gas constant for air, R.

$$P_{net} = h \cdot g \cdot P_{atm} \cdot [(1 / T_o) - (1 / T_i)] / R \quad (23)$$

Assuming that friction is negligible, P_{net} can be used in Bernoulli's equation to calculate the velocity, V, through the stack as:

$$V = \sqrt{2\ P_{net} / \rho} \quad (24)$$

The density, ρ, in Equation 24 can be assumed to be the density of air at the temperature when it exits the stack, to obtain the most conservative result. If the internal temperature profile over the oven's height is known, the internal oven temperature near the top of the opening before the retrofit, $T_{oven,1}$, and after the retrofit, $T_{oven,2}$, are known. The temperature profile could be found by taking temperature measurements along the oven's height. If velocity and temperature of infiltration air, V_{inf1} and T_{inf}, are known, velocity of infiltration air after the retrofit, V_{inf2}, can be found by combining Equation 23 with Equation 24 and creating a velocity ratio. Equation 25 is the resultant equation to calculate V_{inf2}.

$$V_{inf2} = V_{inf1} \cdot \sqrt{(1/T_{inf} - 1/T_{oven,2}) / (1/T_{inf} - 1/T_{oven,1})} \qquad (25)$$

The energy savings, Q_{sav}, is the difference between the energy lost from leakage before and after the retrofit.

$$Q_{sav} = A \cdot Cp_a \cdot [V_{inf1} \cdot \rho_{a1} (T_{oven,1} - T_{inf}) - V_{inf2} \cdot \rho_{a2} (T_{oven,2} - T_{inf})] \qquad (26)$$

Savings Example

We analyzed a cure oven with a high vertical entrance and exit. We measured oven air at a temperature of 450 F to be exfiltrating the oven at an average velocity of 450 ft/min over an area of 8.5 ft^2. If the entrances and exits were lowered, we estimate the temperature at the lower entrances would be about 350 F, and the velocity would reduce to about 409 ft/min. This would reduce total oven energy use by about 28%.

Improving Efficiency by Sealing Leaks or Installing a Back Pressure Damper

Air infiltrates into ovens and furnaces that are not tightly constructed. To minimize infiltration, leaks should be sealed and doors and ports should be well maintained. To further reduce infiltration, backpressure dampers can be installed on exhaust stacks to control the system's pressure so that it is slightly positive. Back pressure dampers can be sophisticated mechanisms with active pressure control, or a simple as blocking a small part of the exhaust stack with a ceramic brick.

Method For Estimating Savings

Excess air and exhaust gas temperature can be measured with a combustion analyzer. If excess air is higher than would be expected from combustion air alone, infiltration most likely takes place in the system. If no ventilation is required in the system, the target would be to eliminate infiltration and bring system excess air to 10%. Equations 12 and 13 can be used to calculate effective combustion temperature and combustion efficiency before and after reducing or eliminating infiltration. Equation 16 can then be used to calculate energy savings.

Savings Example

We analyzed the exhaust gasses from an annealing furnace, and found the temperature to be about 1,700 F and the excess air content to be about 90%, which yields a combustion efficiency of about 31%. Inspection of the furnace shell and the high excess air content suggested that air was infiltrating into the furnace. If the furnace was well-sealed and backpressure dampers were installed to reduce infiltration and bring excess air down to 10%, combustion efficiency would increase to 55%. This would result in a 44% savings in energy use.

SUMMARY AND CONCLUSIONS

This paper identified the three major categories of air flow in combustion process heating systems: combustion air, ventilation air, and infiltration air. It discussed energy saving opportunities related to the management of these air flows, and developed methods for quantifying the expected savings. These methods are based on thermodynamic relationships and can be evaluated using easily measured variables. Case study examples demonstrate that managing air flow in process heating systems can reduce system energy use by as much as 30% - 50%.

In general, the quantity of combustion air should be reduced to about 10% excess air. In addition, combustion air can be preheated with a recuperator, or exhausted ventilation air can be used as combustion air. The quantity of ventilation air should be reduced to the minimum safe level. In addition, air exhausted from thermal oxidizers can be recycled as ventilation air. Infiltration air can be reduced by lowering oven openings or repositioning vertical openings to the oven floor. In addition, infiltration air can be reduced by sealing leaks or installing back-pressure dampers on the exhaust stacks.

Many of these methods have been incorporated into a free public-domain software application, HeatSim, which is available from the University of Dayton Industrial Assessment Center at www.engr.udayton.edu/udiac.

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