Consider Submerged Combustion for Hot Water Production

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Here's a rundown on what submerged combustion is, its advantages and limitations, and how to implement the technology.

Typically hot water is produced in natural-gas-fired boilers, which have an efficiency of 75–85% at best. Several factors limit this efficiency. First, to avoid problems with acid condensation, the exhaust gas from these indirect-fired boilers is kept above 300°F. The benefit of the additional heat-transfer surface area (which requires stainless steel construction) to recover more heat may not justify the expense. Second, the water produced from combustion is kept in the vapor state — an additional tap on the heat of combustion. Finally, heat lost to the atmosphere causes further reduction of efficiency despite efforts to insulate all external surfaces.

Enter submerged combustion, a relatively obscure technology that offers improved thermal efficiency for hot water heating. One author compared submerged combustion to blowing air through a straw in a glass of water. If the air is heated, the rising bubbles will cause the water temperature to increase *(1)*.

The technology

In reality, submerged combustion is more complex than simply blowing hot air through a straw. A fuel/air mixture is ignited in a cylindrical chamber, which is submerged in a liquid solution or slurry. Positive pressure evacuates the chamber of liquid, thereby allowing adequate liquid-free volume for essentially complete combustion before the hot exhaust gases contact the liquid.

When the gases reach the end of the cylinder, they form tiny bubbles that are in intimate contact with the liquid medium. Upon contact with the liquid, sensible heat transfer from the gas bubbles causes a rapid drop in gas temperature and an increase in liquid temperature. At the same time, the exhaust gas becomes saturated in vapor. As the bubbles move toward the surface of the liquid, the hot saturated vapors continue to transfer latent heat to the liquid. At the surface of a unit, the temperature of the liquid and the saturated exhaust gas are within 10°F.

"Perry's Chemical Engineers' Handbook" *(2)* describes submerged-combustion evaporators as "well suited to use with severely scaling liquids." In one application, submerged combustion was shown to be effective when used to concentrate either an ethylene glycol or propylene glycol solution after it removed ice from airplanes. The solution was evaporated from its spent condition of 10–20 wt.% concentration to above 50%, where the solution could be used again. Previously, the glycol solutions were sent for disposal at a cost to the user. The cost savings of replacing and disposing of the glycol more than offset the cost of the fuel to evaporate the solution.

In addition to evaporation, submerged combustion can also be used for sensible heating. In one application, it is used to heat water to recover crude oil from tar sands. The water can be recirculated and reheated to minimize water treatment costs. With submerged combustion, the concern of tube bundle fouling is eliminated. Perry's Handbook suggests that installations are limited to regions with low fuel cost. In reality, it is much easier to justify a more-efficient heating system when fuel costs are high *(2)*.

Efficiency calculations

Using water as the liquid to be heated, assume an inlet water temperature of T_{in} (°F), an outlet water temperature of T_{out} (°F), a liquid or slurry heat capacity of c_p (MMBtu/lb•°F) and a liquid or slurry flowrate of Q (lb/h). The heat transferred to the solution (H_{net}, in MMBtu/h) is calculated (neglecting the volume of water lost out the stack) by:

$$H_{net} = Qc_p(T_{out} - T_{in}) \qquad (1)$$

The thermal efficiency, E, of the system is the useful heat divided by H_{gross} (also in MMBtu/h), the heat added (assuming the amount of fuel consumed is known):

$$E = H_{net}/H_{gross} \qquad (2)$$

For natural gas, the heat from the fuel is taken to be the volume of gas multiplied by the higher heating value of the gas.

Multiple units are often used to provide additional capacity. Furthermore, intermediate streams of liquid may be withdrawn when the liquid has reached a certain concentration or temperature. For example, one installation has three burners, each rated at 13.5 MMBtu/h, in series. The temperatures of the tanks are 105°F, 140°F and 170°F. The plant uses approximately 600–800 gal/min at 105°F as hot water for washing in the plant and an additional 400–600 gal/min at 170°F to drive a chemical reaction.

Efficiency calculations for multiple units involve adding up the water streams where heat is removed. For the above example:

$$H_{net} = c_p[Q_1(T_{out,1} - T_{in}) + Q_2(T_{out,2} - T_{in})] \qquad (3)$$

where Q_1 and $T_{out,1}$ are the flowrate and temperature of water taken from the first unit and Q_2 and $T_{out,2}$ are the flowrate and temperature of water taken from the last unit.

Some of the water in the saturated vapor comes from the combustion process. For aqueous solutions or slurries, the stack gas will require additional water from the liquid to become saturated. As the gas temperature increases, the amount of water vapor required to saturate the gas stream increases exponentially, as demonstrated by psychrometric data (see table). Water vapor out the stack represents lost heat. Therefore, the overall efficiency of submerged combustion depends on the temperature of the gas leaving the liquid medium.

Table. Psychrometric data.

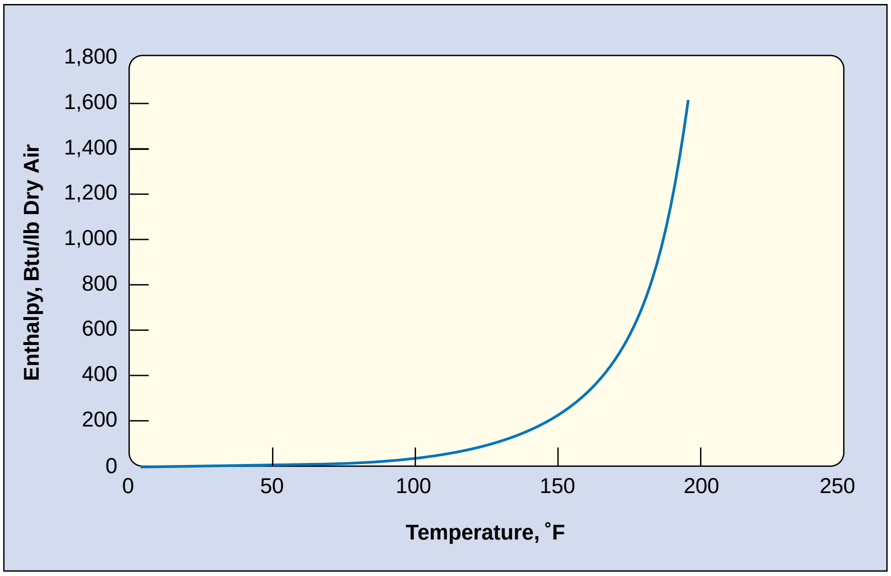
Temperature (°F)	Humidity Ratio (lb_m water/lb_m dry air)	Enthalpy (Btu/lb_m dry air)
32	0.004	4.1
41	0.005	5.9
50	0.008	8.3
59	0.011	11.6
68	0.015	16.1
77	0.020	22.1
86	0.027	30.0
95	0.037	40.5
104	0.049	54.4
113	0.065	72.7
122	0.087	96.8
131	0.115	129.0
140	0.154	172.3
149	0.206	231.7
158	0.279	315.4
167	0.386	438.0
176	0.553	628.7
185	0.838	956.0
194	1.420	1625.1

For example, the table shows that for an increase in stack gas temperature from 95°F to 104°F, the enthalpy increases from 40.5 to 54.4 Btu/lb dry air, a difference of 13.9 Btu/lb. However, an increase of another 9°F to 113°F translates to an 18.3 But/lb increase, from 54.4 to 72.7 Btu/lb. The enthalpy increase of a stack temperature change from 104°F to 113°F is 32% more than that from 95°F to 104°F, and the difference increases faster as temperatures increase (Figure 1).

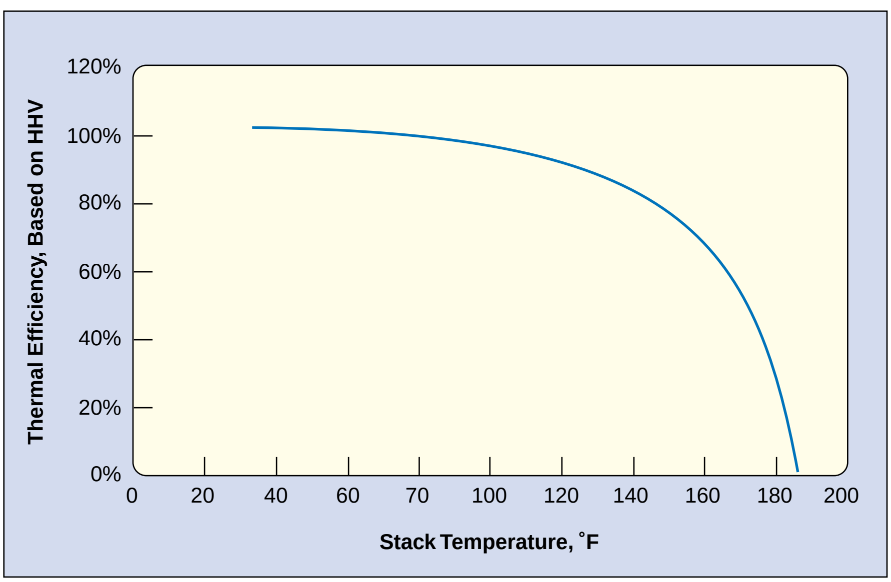
As the heated liquid temperature increases, the stack gas temperature also goes up. Heat lost out the stack is mostly water vapor. For example, 1 lb of saturated dry stack gas at 86°F contains 0.027 lb water, while air at 149°F contains 0.206 lb water. The theoretical efficiency (assuming negligible heat losses) of a single burner that heats water or an aqueous solution is 97.6% at 86°F and 77.4% at 149°F. This efficiency is essentially independent of inlet water temperature.

Based on similar calculations, an efficiency curve can be plotted as a function of the outlet stack temperature (Figure 2). At lower stack temperatures, the system efficiency approaches 100%, because the enthalpy of ambient air at a higher temperature and humidity contributes to the overall energy balance. If the overall system efficiency is to be kept above 90%, the stack temperature must stay below 124°F. Including other variables, such as ambient air temperature and humidity, amount of excess air, air pressure (elevation), and different types of fuel, should result in more-precise efficiency calculations.

Note also that the efficiency of a submerged combustion unit is 0% at approximately 187°F. At this temperature, all of the heat from combustion is used for saturating the stack gas. Therefore, 187°F is theoretically the highest temperature achievable by submerged combustion technology for



■ Figure 1. Enthalpy vs. temperature of air saturated in water vapor.



■ Figure 2. Higher heating value efficiency curve.

hot water applications. In reality, 170–180°F is realistically achievable for water.

Fluids with lower vapor pressures can be heated to higher temperatures. For example, an aqueous solution containing 30 wt.% magnesium chloride, which has a much lower vapor pressure than water, can be heated to above 187°F. The heat of combustion causes the magnesium chloride concentration to increase because of the loss of water in the saturated stack gas.

When the design of a submerged combustion system requires outlet liquid temperatures higher than 124°F, a heat recovery unit will lower the stack temperature and improve the overall efficiency. The benefit of heat recovery must be compared with the capital cost. The cold inlet water is first routed through the heat recovery unit, where the stack gas from the submerged combustion system mixes directly with the water. Multiple submerged combustion units can send their stack gases to the same heat recovery unit.

Advantages

In addition to the efficiency benefit discussed above, submerged combustion has several additional advantages:

It is ideal for liquids that tend to foul or scale. Sludge can be heated without concern for fouling of tubes. Saltwater solutions can be concentrated — as the water is evaporated, small amounts of insoluble salts, which would normally foul shell-and-tube heat exchangers in a matter of hours, may precipitate. Submerged combustion eliminates concerns for fouling of indirect heating surfaces. Although the cylindrical burner in the solution needs to be cleaned from time to time, the cleaning is far easier than hydroblasting tubes.

It operates near atmospheric pressure. Safety is improved because there are no high-pressure vessels.

It requires minimal supervision. Unlike traditional boilers, which often require full-time supervision, submerged combustion needs little attention. Automatic temperature controllers can adjust the fuel and air to maintain a temperature setpoint. Alternatively, burners can be configured to run at maximum capacity full-time, especially when high volumes of water are being heated and the temperature increase is minimal. At a mine in Canada, 10 burners rated at 13 MMBtu/h each are used for 15,000 gal/min of brine with a temperature rise of 18°F. These burners run at maximum capacity. If brine flow decreases, burners are shut down to maintain a desired temperature.

Greenhouse gases are reduced. Higher efficiencies result in lower fuel consumption and lower CO_2 emissions.

Disadvantages and limitations

While the higher efficiencies make submerged combustion initially appealing, it is not the right technology for all applications. Consider the following disadvantages:

Cooling water may be needed. For large burners (larger than 8 MMBtu/h), cooling water may be required. The heat transferred to the cooling water can be recovered, if the water can be sent into the tank being heated. For concentrating aqueous solutions, the heat will be lost. Cooling water may require additional pumping, additional water consumption, and more problems with keeping burners operating (since cooling water temperature must be maintained below a certain level to keep burners running). Chemical or mechanical cleaning of the heating jacket may be required to remove mineral deposits.

Separate heat-recovery equipment may be necessary. Separate heat recovery is required to maintain efficiencies greater than 90% above 124°F. Additional equipment means more capital investment.

The maximum water temperature is 180°F. For most aqueous applications, submerged combustion is limited to 180°F due to the vapor pressure of water. For solutions with lower vapor pressures, bench or pilot testing is required to evaluate the benefits of submerged combustion.

It is not a steam replacement. Submerged combustion will not necessarily replace steam, unless steam is used to heat or evaporate water.

Submerged combustion produces a low pH. In aqueous solutions, a low solution pH is created by bubbling CO_2 from the exhaust gas through water. The slight positive pressure of the tanks keeps the CO_2 in solution, where carbonic acid is formed. However, measurements show that the pH quickly returns to that of the original solution when the pressure is released.

Vibration control is required. For a 13.5 MMBtu/h burner, the cylindrical combustion chamber extends more than 6 ft below the point of attachment to the lid. The blower is designed to evacuate this cylinder to allow combustion. The combination of combustion and positive pressure creates waves in the chamber, and the overall vibration can be violent if the unit is unsupported. Additional supports may be required for the bottom of the cylinder and the top. One installation without supports at the bottom of the cylinder showed cracking of the cylindrical walls and required substantial repair.

It cannot be used with flammable solutions.

Implementation

If submerged combustion appears to be the right technology based on a consideration of the above criteria, the first step is to determine the heating load. One must calculate the heating load required in the process and apply an appropriate efficiency to find the total heat required. Fuel savings can also be calculated using an appropriate efficiency for other technologies. With the recent escalation of natural gas costs, justification for submerged combustion is far easier than it would have been several years ago.

The material of construction must also be considered. Carbon and stainless steels have been used in many applications, but more corrosion-resistant alloys could be used. Vibration control must be paramount in the design of a system, especially above 8 MMBtu/h.

For burner capacity, the critical design issue is flame length. If the flame length is too long (meaning the cylindrical burner chamber is too short), the flame will be cooled prematurely causing high CO problems. Consider the need for environmental permitting of a submerged combustion system, and allow adequate time for state and/or federal approval.

One design for submerged combustion used a mechanically linked air and gas valve. The system was tuned like any typical natural gas burner, where either the gas or air flowrates are adjusted to minimize CO and to minimize excess oxygen in the stack gas. However, the problem with this traditional method is that when the ambient air temperature changes either seasonally or from day to night, the air-to-fuel mixture would be adversely affected. One new submerged combustion design provides for an automatic-tuning system to adjust the air flow and the gas flow independently using pressure differential.

For heating water and most aqueous solutions, vendors should have adequate experience. However, for evaporative applications or exotic solutions, pilot testing is highly recommended to minimize risks. Vendors of submerged combustion equipment can assist with the details (*e.g.*, burner selection, process control, safety considerations, etc).

Concluding thoughts

As energy consumers search for more efficient methods to produce steam and heat, submerged combustion could be considered as an alternative to steam. The higher efficiencies often result in a payback period of less than two years, even for replacements of existing lower-efficiency boilers. CEP

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