**NATURE AND UTILITY
OF SOME UNSTEADY CHARACTERISTICS
OF A FOSSIL-FUEL-FIRED BOILER**

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DEPARTMENT OF ENERGY AND ENVIRONMENT

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ABSTRACT

The dimensionless temperature rise rate of an initially cold fossil-fuel-fired boiler and the boiler's off-cycle cooling rate are examined analytically. If the thermal relaxation times for the non-water-containing boiler elements are to be relatively short, simplified expressions are found for the time variation of the dimensionless boiler temperature. The utility of these analytic results is examined in the light of experimental observations.

INTRODUCTION

It has been reported¹ that the rate of rise of boiler water temperature is approximately constant in time after a brief initial transient, when a cold residential boiler is heated by a steady combustion source. The boiler in question served no external load. It is also reported¹ that the boiler cool-down period (after achievement of a peak desired temperature) corresponds to an exponential decay of boiler water temperature with time. The purpose of this study is to examine the gross heat transfer, thermal storage, and energy release rate mechanisms which underlie these observations.

The heating of a cold boiler "to temperature" by a quasi-steady combustion process involves time-dependent heat transfer within and thermal energy storage in the nonuniform, nonisothermal boiler. In the usually accepted sense, the process is nonsteady. This despite the quasi-steady combustion process. Nevertheless, the reported observations indicate certain regularities in major portions of the time periods which describe the "heat-up" and "cool-down" processes. It is interesting to examine, then, the physical nature of these regularities and their relation, if any, to the boiler's steady state characteristics (e.g., steady state efficiency).

It is also known that a boiler's cycle efficiency is related to its "cool-down" characteristics. Accordingly, it is interesting to examine the relations, if any, between "cool-down" regularities and "cycle efficiency."

BOILER "HEAT-UP" FROM COLD INITIAL CONDITIONS - SUBJECT TO NO HEATING LOAD

A typical residential boiler consists of a spatially nonuniform distribution of material elements. Each element has its own thermophysical properties. At initial time, the system is taken to be isothermal (cold) and its total enthalpy and enthalpy distribution are deducible, once its detailed internal structure and material constituency are known. Immediately after ignition, the system is highly nonisothermal and nonsteady. Nevertheless, its instantaneous elemental and total enthalpy are well defined and deducible if the complete time-dependent temperature field is specified. In general, the complete time-dependent temperature field is not sufficiently well investigated to be "known." It is, however, useful to study the gross physical features of the boiler's heat-up period and to examine whether certain approximate truths are implied by the aforementioned¹ observations. Consider the disposal of enthalpy resulting from the heat liberated by the combustion process, where the rate of combustion heat release is steady and the entire system is initially at (T_0) .

$$\dot{m}_f \Delta_c = h_{f,B}(T_f - T_B) + h_{f,j}(T_f - T_A) + h_{\text{stack}} \left(\frac{T_f + a\bar{T}_B}{2} - T_A \right) = \text{constant} \quad (1)$$

where

$\dot{m}_f$ = steady state mass flow rate of fuel,

Δ_c = heat of combustion,

$h_{f,B}$ = effective heat transfer coefficient between the flame gases and the heat exchanger,

a = a constant,

$h_{f,j}$ = effective heat transfer coefficient for heat losses through the jacket of the combustion chamber,

$h_{B,j}$ = effective heat transfer coefficient for heat losses through the jacket due to the boiler's heat exchanger/water reservoir,

h_{stack} = effective heat transfer coefficient for the stack losses,

T_A = ambient temperature,

T_f = adiabatic flame temperature, and

T_B = characteristic boiler (reservoir) temperature.

Considering the instantaneous disposition of energy to the boiler,

$$h_{f,B}(T_f - T_B) = \frac{d}{dt} \int \bar{m}_{B,i} c_{p,i} (\bar{T}_{B,i} - T_o) + h_{B,j}(T_B - T_A) . \quad (2)$$

From Eqs. (1) and (2),

$$\begin{aligned} \dot{m}_f \Delta_c = \frac{d}{dt} \int \bar{m}_{B,i} c_{p,i} (\bar{T}_{B,i} - T_o) + h_{stack} \frac{T_f + a \bar{T}_{B,i}}{2} - T_A \\ + h_{B,j} (\bar{T}_B - T_A) + h_{f,j} (T_f - T_A) . \end{aligned} \quad (3)$$

We may define an efficiency, η_q , in terms of the effectiveness of the rate of enthalpy storage in the boiler, compared with the rate of energy release by the combustion process,

$$\eta_q = \frac{\frac{d}{dt} \int \bar{m}_{B,i} c_{p,i} \bar{T}_{B,i}}{\dot{m}_f \Delta_c} \quad (4)$$

$$\eta_q = \frac{\bar{m}_{B,1} \dot{c}_{p,1} \bar{T}_{B,1} + c_{p,1} \dot{\bar{T}}_{B,1} + \bar{m}_{B,2} \dot{c}_{p,2} \bar{T}_{B,2} + c_{p,2} \dot{\bar{T}}_{B,2} + \dots}{\dot{m}_f \Delta_c} \quad (5)$$

In general, the numerator is time (or temperature) dependent whereas the denominator is not. In general, η_q is not a constant.

If, after some given (initial) time period, all $\bar{m}_{B,i}$ values but one have come (approximately) to a quasi-steady condition, then Eq. (5) becomes

$$\eta_q = \frac{\dot{m}_{B,1} \left[(\dot{c}_{p,1}) T_{B,1} + (c_{p,1}) (\dot{T}_{B,1}) \right]}{\dot{m}_f \Delta_c} \quad (6)$$

If, additionally, the only nonequilibrated component is the boiler water (and its immediate envelope), then, since $c_{p,1}$ varies by only some 2% over the temperature range of boiler operation,

$$\eta_q \approx \left(\frac{\dot{m}_{B,1} c_{p,1} \dot{T}_{B,1}}{\dot{m}_f \Delta_c} \right)$$

It has been reported¹ for a number of observations that

$$\dot{T}_{B,1} = \text{constant}$$

over a substantial period of the heating of a boiler (from ambient to "temperature"). If so, η_q is also constant. The assumption that thermal equilibration of all m_i (except m_1) has occurred after some time implies that

$$h_{f,j}(T_f - T_A) = \text{constant, after an "initial" period,}$$

$$h_{B,j}(T_B - T_A) \text{ varies linearly with } T_B, \text{ and}$$

$$h_{\text{stack}} \left(\frac{T_f + aT_B}{2} - T_A \right) \text{ varies linearly with } T_B.$$

Then

$$\dot{m}_f \Delta_c = h_{f,B}(T_f - T_B) + \text{cost} + h_{B,j}(T_B - T_A) + h_{\text{stack}} \left(\frac{T_f + aT_B}{2} - T_A \right)$$

$$= \text{a linear function of temperature - but also a constant.} \quad (7)$$

Consequently, from Eq. (2),

$$h_{f,B}(T_f - T_B) \approx \dot{m}_{B,1} c_{p,B} \dot{T}_B \quad (8)$$

and

$$\begin{aligned} 0 &= -h_{f,B} \dot{T}_B + h_{B,j} (\dot{T}_B) + \frac{a}{2} h_{\text{stack}} (\dot{T}_B) \\ &= (h_{B,j} + \frac{a}{2} h_{\text{stack}} - h_{f,B}) \dot{T}_B, \end{aligned} \quad (9)$$

or

$$h_{f,B} = h_{B,j} + \frac{a}{2} h_{\text{stack}} , \quad (10)$$

∴ from Eqs. (8) and (10)

$$(h_{B,j} + \frac{a}{2} h_{\text{stack}})(T_f - T_B) = \overline{m_B c_{p,B}} \dot{T}_B$$

$$\boxed{\frac{dT_B}{dt} = \frac{h_{B,j} + \frac{a}{2} h_{\text{stack}}}{\overline{m_B c_{p,B}}} (T_f - T_B)} \quad (11)$$

and the rate of rise of boiler temperature is not a constant (it is an exponential). But if $T_f \gg T_B$, then $dT_B/dt \approx$ over a small range of T_B values.

Equation (11) has the solution

$$T_B = T_f - A \exp [-\mu t] \quad (12)$$

where

$$\mu = \left[\frac{h_{B,j} + \frac{a}{2} h_{\text{stack}}}{\overline{m_B c_{p,B}}} \right] \quad (13)$$

When values of T_B can be experimentally measured over a range of validity of Eq. (12), then, for $t_1 \leq t \leq t_2$, both A and μ can be determined.

The Efficiency, η_q :

If the assumptions leading to Eq. (6) are applicable during the period $t_1 \leq t \leq t_2$ the Eqs. (6) and (11) yield

$$\eta_q = \frac{\overline{m}_{D,1} \left[\dot{c}_{p,1} T_{D,1} + c_{p,1} \mu (T_f - T_{B,1}) \right]}{\dot{m}_f \Delta_c} \quad (14)$$

As noted earlier, the denominator is time invariant but the numerator, in general, is not. If, however, one assumes that $\dot{c}_{p,1}$ is very small because

- (a) the effective specific heat of the reservoir is due primarily to water, with a very small contribution by the reservoir envelope, and
- (b) the effective specific heat of the reservoir is almost independent of temperature in the T_B range of interest,

then

$$\eta_q \approx \frac{\bar{m}_{B,l} c_{p,l} \mu (T_f - T_{B,l})}{\dot{m}_f \Delta_c} \quad (15)$$

The Steady State Efficiency, η_s , and Steady State Boiler Operation:

Under conditions of steady state boiler operation,

$$\dot{m}_f \Delta_c = h_{f,B} (T_f - T_B) + h_{f,j} (T_f - T_A) + h_{\text{stack}} \frac{T_f + a \bar{T}_B}{2} \quad (16)$$

and

$$h_{f,B} (T_f - T_B) - h_{B,j} (T_B - T_A) = \eta_s \dot{m}_f \Delta_c \quad (17)$$

and

$$\eta_s = \frac{h_{f,B} (T_f - T_B) - h_{B,j} (T_B - T_A)}{\dot{m}_f \Delta_c} \quad (18)$$

If the reservoir jacket losses are small, then

$$\eta_s \approx \frac{h_{f,B} (T_f - T_{B,l})}{\dot{m}_f \Delta_c}$$

and η_s is proportional to η_q ; namely,

$$\frac{\eta_s}{\eta_q} \approx \frac{h_{f,B}}{h_{B,j} + \left(\frac{a}{2}\right) h_{\text{stack}}} \quad (19)$$

Note that the constant of proportionality is dependent on the specifics of the boiler and need not be the same for all boilers.

Experimental determination of the approximately steady value of η_q by Eq. (15) may be used with experimental determination of η_s (jacket losses neglected) by Eq. (16) to determine

$$\left[\frac{h_{f,B}}{\bar{m}_{B,l} c_{p,l} \mu} \right]$$

or

$$\left[\frac{h_{f,B}}{h_{B,j} + \frac{a}{2} h_{\text{stack}}} \right]$$

A Boiler's Off-Cycle Losses:

A boiler's off-cycle losses derive from a combination of jacket losses and free convective losses. Let us define

$\overline{C M}$ = average enthalpy per degree of the boiler,

$\overline{T}$ = characteristic boiler temperature,

h_j = off-cycle jacket heat transfer coefficient,

h_c = off-cycle convective heat transfer coefficient,

t = time scale for OFF cycle,

$\frac{\overline{T} - T_a}{\overline{T}_{\max} - T_a}_o$ = dimensionless characteristic boiler temperature,

and subscripts

o = time equals zero (beginning of OFF cycle),

c = free convection, and

j = jacket.

Then we can write a simple time-dependent energy conservation equation which describes the cooling rate of the boiler, during the OFF cycle. Note that none of the physical variables requires any knowledge of stack gas temperature:

$$\overline{C M} \left(\frac{d\overline{T}}{dt} \right) = -h_j (\overline{T} - T_a) - h_c (\overline{T} - T_a); \quad (20)$$

then

$$\left(\frac{d\overline{T}}{dt} \right) = - \left[\frac{h_j + h_c}{\overline{C M}} \right] (\overline{T} - T_a)$$

or

$$\frac{d(\overline{T} - T_a)}{(\overline{T} - T_a)} = - \left[\frac{h_j + h_c}{\overline{C M}} \right] dt$$

and

$$\ln(\overline{T} - T_a) = - \left(\frac{h_j + h_c}{\overline{C M}} \right) (t - t_o), \quad (21)$$

$$(\bar{T} - T_a) = A \exp - \frac{h_j + h_c}{\frac{C M}{P}} t \quad (22)$$

For $t = 0$,

$$(\bar{T} - T_a) = (\bar{T}_{\max} - T_a)_0 = A; \quad (23)$$

thus,

$$\frac{\bar{T} - T_a}{(\bar{T}_{\max} - T_a)} = \exp - \left[\left(\frac{h_j + h_c}{\frac{C M}{P}} \right) t \right] \quad (24)$$

In general, $\bar{T}$ and $\frac{C M}{P}$ are experimentally unknown prior to the completion of the boiler's thermal equilibration, which occurs during the period $0 \leq t \leq \tau_e$ where τ_e = equilibration period).

This provides expected experimental results such as those illustrated in Figure 1.

Figure 1. Cooling curve for off-cycle losses.

Eq. (24) and Figure 1 show that the the rate of off-cycle cooling is exponential in time with a decay coefficient which is determined primarily by the heat transfer coefficients for the off-cycle jacket losses and for the off-cycle free convective losses.

Inasmuch as cooling curves of the type shown in Figure 1 are experimentally determinable for any given boiler system, quantitative measurements can be made on the off-cycle performance of various boilers as well as various boiler refit actions. Some of these are discussed below.

Consider a boiler whose cooling curve has been observed, thereby yielding $S_A = -(h_j + h_c)/(C M)$ for the boiler. The boiler may then be fitted (in the laboratory) with a^P fast-acting, insulated ("perfect") stack vent damper and the cooling curve redetermined. This corresponds to the case where $h_c = 0$ and the cooling curve slope is given by

$$S_B = -(h_j / \overline{C M}_P).$$

The "perfect" stack vent damper may then be removed and the boiler heavily insulated. Determination of the resulting cooling curve corresponds to $h_j \approx 0$ and

$$S_C = -(h_c / \overline{C M}_P).$$

The experimental knowledge of S_A , S_B , and S_C may then be used to find h_j , h_c , and $C M$ for the boiler. These are the characteristics which determine the cooling curve for the unmodified boiler.

Consider now that the effectiveness of a given stack vent damper installation is to be assessed. Install and operate the stack vent damper as desired and experimentally determine

$$S_D = -(h_j + h_c^*) / \overline{C M}_P$$

where

h_c^* = the modified heat transfer coefficient for the free convective losses for the system.

Inasmuch as S_D , h_j , and $\overline{C M}_P$ are known, the experiment then determines, h_c^* for the modified system.

Thus, by a series of experiments on off-cycle cooling curves, the performance merits of various devices designed to decrease h_c is determinable.

The Retention-Head Burner and the Suppression of Off-Cycle Losses:

It is expected that a retention-head burner, substituted for an ordinary burner, will decrease the h_c value for the system. This effect is due to the suppression of air leaks at the bottom of the boiler. Quantitatively, this effect is measurable by experimental study of the boiler's cooling curve during the off-cycle period. When a retention-head burner is substituted for an ordinary one and the off-cycle cooling curve redetermined, h_c^{**} is directly deduced. One may define a figure of excellence for a convection loss inhibitor retrofit:

$$\epsilon_c^{**} \equiv \left[\frac{h_c - h_c^{**}}{h_c} \right] \quad (25)$$

where $0 \leq \epsilon_c \leq 1$. Here $\epsilon_c = 0$ corresponds to no improvement and $\epsilon_c = 1$ corresponds to the maximum possible improvement.

Similar kinds of experiments may be performed to evaluate the effectiveness of improved jacket insulation. Here, a corresponding figure of excellence for a jacket loss inhibitor retrofit is

$$\epsilon_j^* \equiv \left(\frac{h_j - h_j^*}{h_j} \right) \quad (26)$$

where $0 \leq \epsilon_j^* \leq 1$. Here $\epsilon_j = 0$ corresponds to no improvement and $\epsilon_j^* = 1$ corresponds to the maximum possible improvement.

Summary Remarks:

A boiler that is heated by a steady state combustion process, but is not delivering hot water to a load, has been found to display a characteristic internal enthalpy storage rate pattern. One may define η_q to be the ratio of this enthalpy storage rate to the rate of energy release by the combustion process. Under special circumstances, η_q is found to be approximately constant. In general, η_q is not equal to η_s , the classical steady state efficiency.

This study also considered the character of a boiler's standby cooling rate, when it is not serving a load and when it is not being heated by the combustion process. Equation (24) and Figure (1) provide quantitative statements of this standby cooling rate law. The boiler's dimensionless temperature is found theoretically to decay in time, according to an exponential decay law. This is in agreement with the experiment findings of reference (1). Prime determinants of the exponential decay rates are the heat transfer coefficients for the off-cycle jacket losses and for the off-cycle natural convective losses.