A stylized sunburst graphic with a white semi-circle on the right side and several white triangular rays of varying lengths extending from it into a black rectangular background.

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ON THE CONCEPT OF A REVERSIBLE FLAME

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ABSTRACT

Conceptually, a reversible flame is obtained by preheating a mixture of reactants to a given temperature T_b and pressure p_b , while maintaining inhibited by some means all the chemical reaction mechanisms. The mixture must have a composition exactly equal to that dictated by the chemical equilibrium condition at the given temperature and pressure. Once the mixture has been preheated to T_b and p_b , “turning on” the chemical reaction mechanisms has no effect because the composition is already that of chemical equilibrium. Subsequent cooling of the reacting mixture will shift the chemical equilibrium composition and gradually liberate the chemical exergy of the fuel. Original discussions by Keenan [1] and Obert [2] present the concept as highly theoretical due to the fact that the values of T_b at which a reversible flame is possible are extremely high. However, by examining the concept in some detail, we show that in principle a reversible flame is possible at any given value of T_b . We hope that this observation will fuel further investigations on the practical applicability of the concept.

1. INTRODUCTION

In combustion flames, a large fraction of the fuel exergy is destroyed by irreversibility. Depending on parameters such as excess air, preheating of the reactants, exhaust gas recirculation, and other combustion conditions, for hydrocarbon combustion in conventional power plants about 50% of the fuel exergy is destroyed by the irreversibility of the flame and the subsequent heat transfer to the power plant working fluid. It is clear that understanding the influence of the various parameters may lead to new ideas for improving the thermodynamic efficiency of fossil fuel utilization.

In this paper we discuss the concept of “reversible combustion” that can be traced back to Keenan[1]: “In order to change a mixture of reactants (such as C and O₂) to products (such as CO₂) reversibly, we might first bring the mixture reversibly to a state in which the reactants could coexist in stable equilibrium with an infinitesimal amount of the products — that is, a state in which the tendency toward chemical

equilibrium has vanished. Then the mixture could be gradually and reversibly altered in pressure and temperature, ..., while it follows a path of most stable states of progressively greater degrees of combination.”

The idea has been taken one step forward by Obert[2]: “Although no practical method exists for reversibly operating an internal combustion engine, a theoretical means can be imagined as proposed by Keenan. Suppose that a mixture of fuel and air were isentropically compressed to an extremely high temperature. (It is assumed that the speed of the compression process is extremely swift and therefore reaction does not occur during the compression [or else a negative catalyst is present]). At this high temperature, once achieved (although quite imaginatively), reaction could not occur to any great extent ... Then the mixture can be slowly and isentropically expanded; as temperature falls, reaction proceeds reversibly; and ... a greater and greater amount of products will be formed.”

Another suggestion was given by Keenan[1]: “If it is difficult to attain a stable state of complete dissociation (as it is for C and O₂) it might be necessary to find a chain of reactions involving other substances. For example, the fuel might be combined with some third material with which it will react reversibly. If the products of this reaction will unite reversibly with air to restore the third material to its initial state and leave only the usual products of combustion, then the products could be formed reversibly from fuel and air.”

The suggestion has been recently picked up and developed by Richter and Knoche[3] who suggest the use of a metal oxide as a “third material” and introduce a useful representation of the states of reactants and products of combustion on an enthalpy versus entropy graph.

In this paper, we develop such graphical representation as a means to clarify the theoretical concept of a “reversible flame.” Rather than focusing on the use of a third material, here we focus on the idea of “turning on and off” the chemical reaction mechanisms.

Conceptually, a reversible flame is obtained by preheating a mixture of reactants to a given temperature T_b and pressure p_b , while maintaining inhibited by some means all the chemical reaction mechanisms. The mixture must have a composition exactly equal to that dictated by the chemical equilibrium condition at the given temperature and pressure. Once the mixture has been preheated to T_b and p_b , “turning on” the chemical reaction mechanisms has no effect because the composition is already that of chemical equilibrium. Subsequent cooling of the reacting mixture will shift the chemical equilibrium composition and gradually liberate the chemical exergy of the fuel.

A major practical difficulty is to maintain all reactions inhibited during preheating. A way to prevent at least some of the reactions is to preheat the reactants in separate streams, and then mix them. In this case the only irreversibility inherent in the method is that due to isothermobaric mixing. The consequent loss is not a large fraction of the fuel exergy provided the mole fraction of the fuel in the resulting mixture is not too small.

For standard hydrocarbons, a reversible flame is unpractical because it requires either an extremely high preheating temperature or an extreme dilution of the hydrocarbon in the reactant streams. However, the concept is appealing enough to suggest that further research should address these difficulties. For the concept of a

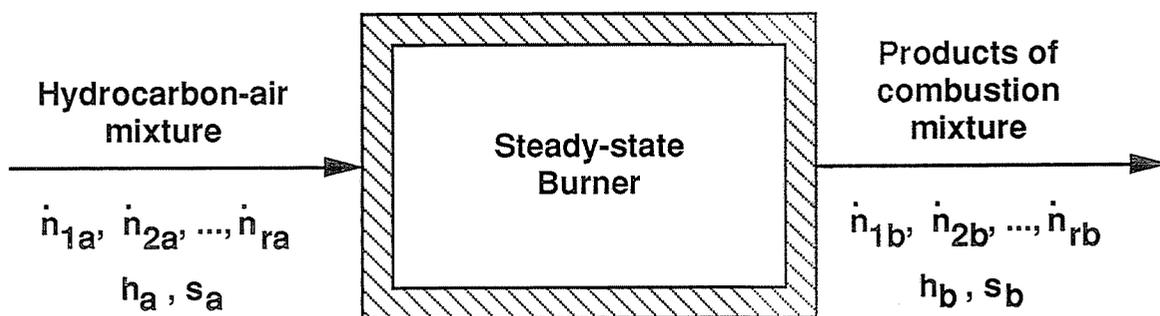


Figure 1.

reversible flame to become practical, we need to identify a suitable reaction scheme (and the related fuel preprocessing) that allows to reach a value of T_b attainable by current-technology materials for a not-too-high dilution of the fuel in the reactants, and such that the reactions can be effectively “frozen” during preheating (by either separate preheating or some kind of anticatalyst or reaction inhibitor) and effectively “promoted” during cooling (by some kind of catalyst or reaction promoter). Reaction inhibitors and promoters have been the subject of several combustion studies[4].

Weinberg[4] summarizes the underlying trend of combustion research as an effort to gain more and more controllability, allowing ourselves to vary the temperature of the reaction zone, and beyond that, the rate of reaction independently of the fuel/air ratio, and also to vary the rate of the reactions which produce pollutants independently of the rate of energy release. As a result of our discussion of the theoretical concept of a reversible flame we conclude that an effort may be worthwhile to gain also another controllability, allowing ourselves to inhibit the rate of reactant dissociation during preheating and to promote the rate of combustion during cooling so as to vary the entropy production by irreversibility.

2. NORMALIZED ENTHALPY VS ENTROPY GRAPH

In this section, by reviewing some standard results[5] we build up the notation that is needed to develop a useful enthalpy versus entropy graph, introduced by Richter and Knoche[3].

We consider an ideal steady-state burner, perfectly insulated, as sketched in Figure 1. The burner is fed with an inlet stream consisting of a bulk-flow state of a mixture of a hydrocarbon fuel, C_kH_ℓ , and air, O_2 and N_2 . The energy balance for the perfectly insulated burner is

$$\dot{n}_b h_b - \dot{n}_a h_a = 0 \quad (1)$$

where \dot{n}_a and \dot{n}_b are the inlet and outlet molar flow rates, and h_a and h_b the specific molar enthalpies of the inlet and outlet mixtures. Equation 1, for given inlet flow rates of constituents, \dot{n}_{ia} , inlet temperature, T_a , inlet pressure, p_a , outlet pressure, p_b , and the condition of complete oxidation of the hydrocarbon, defines the temperature T_b that is called the “adiabatic flame temperature”[5].

Assuming ideal gas mixture behavior for both the inlet and the outlet mixtures,

Table 1. Stoichiometry of the combustion and dissociation reaction mechanisms.

i	constituent	$\nu_i^{(1)}$	$\nu_i^{(2)}$	$\nu_i^{(3)}$	$\nu_i^{(4)}$
1	C_kH_ℓ	-1	0	0	0
2	O_2	$-(k + \frac{\ell}{4})$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$
3	N_2	0	0	0	$-\frac{1}{2}$
4	H_2O	$\frac{\ell}{2}$	0	-1	0
5	CO_2	k	-1	0	0
6	CO	0	1	0	0
7	H_2	0	0	1	0
8	NO	0	0	0	1

the energy balance (Equation 1) becomes[6]

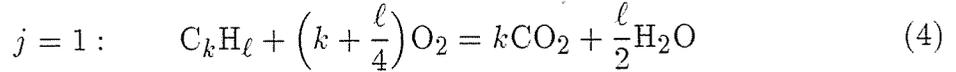
$$\begin{aligned}
 & \dot{n}_b h_b - \dot{n}_a h_a \\
 &= \sum_{i=1}^r \dot{n}_{ib} [h_{ii}(T_b) - h_{ii}(T_o)] \\
 & - \sum_{i=1}^r \dot{n}_{ia} [h_{ii}(T_a) - h_{ii}(T_o)] + \sum_{i=1}^{\tau} \dot{\epsilon}_j (\Delta h^o)_j = 0
 \end{aligned} \tag{2}$$

where the enthalpy of the j -th reaction at standard temperature and pressure

$$(\Delta h^o)_j = \sum_{i=1}^r \nu_i^{(j)} h_{ii}(T_o) = \sum_{i=1}^r \nu_i^{(j)} (\Delta h_f^o)_i \tag{3}$$

$(\Delta h_f^o)_i$ is the enthalpy of formation of the i -th constituent, $\nu_i^{(j)}$ the stoichiometric coefficient of the i -th constituent in the j -th reaction mechanism, and we label the constituents as summarized in Table 1.

For the purpose of evaluating adiabatic flame temperatures, a very good approximation is to consider as active only the hydrocarbon oxidation mechanism



and the dissociation reactions



with the conditions that the hydrocarbon is fully oxidized, i.e., $\dot{\epsilon}_1 = \dot{n}_{1a}$, and that the mixture of products of combustion satisfies the chemical equilibrium equations for each of the dissociation reactions, that is,

$$\frac{y_{6b}(y_{2b})^{1/2}}{y_{5b}} = \left(\frac{p_o}{p_b}\right)^{1/2} K_2(T_b) \quad (8)$$

$$\frac{y_{7b}(y_{2b})^{1/2}}{y_{4b}} = \left(\frac{p_o}{p_b}\right)^{1/2} K_3(T_b) \quad (9)$$

$$\frac{y_{8b}}{(y_{2b})^{1/2}(y_{3b})^{1/2}} = K_4(T_b) \quad (10)$$

where y_{ib} denotes the mole fraction of the i -th constituent in the outlet mixture, and $K_j(T_b)$ the value of the equilibrium constant of the j -th reaction at temperature T_b .

For given values of \dot{n}_{ia} , T_b , p_b , and $\dot{\epsilon}_1$, Equations 8, 9 and 10, together with the stoichiometric relations

$$\dot{n}_{ib} = \dot{n}_{ia} + \nu_i^{(1)}\dot{\epsilon}_1 + \nu_i^{(2)}\dot{\epsilon}_2 + \nu_i^{(3)}\dot{\epsilon}_3 + \nu_i^{(4)}\dot{\epsilon}_4 \quad (11)$$

determine the values of the reaction coordinates $\dot{\epsilon}_2$, $\dot{\epsilon}_3$, and $\dot{\epsilon}_4$, of the dissociation reactions. For given values of \dot{n}_{ia} , T_a , T_b , p_b , and $\dot{\epsilon}_1$, Equations 2, 8, 9, 10 and 11, together with data for the specific heats of the various constituents as a function of temperature[5], determine the adiabatic flame temperature T_b and the reaction coordinates $\dot{\epsilon}_2$, $\dot{\epsilon}_3$, and $\dot{\epsilon}_4$.

The specific exergy (or availability) of a bulk-flow stream of an unburnt mixture of a hydrocarbon and air at standard conditions of temperature $T_o = 25^\circ C$ and pressure $p_o = 1$ atm, with respect to an environment also at standard conditions is very well approximated by the negative of the Gibbs free energy of the oxidation reaction at standard conditions, that is,

$$\dot{E}x_{\text{fuel}} = -\dot{n}_{1a}(\Delta g^o)_1 = -\dot{n}_{1a}[(\Delta h^o)_1 - T_o(\Delta s^o)_1] \quad (12)$$

If the stream is preheated at a temperature T_a and a pressure p_a , the additional exergy rate is

$$\begin{aligned} \dot{E}x_{\text{preheat}} &= \dot{E}x_a - \dot{E}x_{\text{fuel}} \\ &= \dot{n}_a[h_a(T_a) - T_o s_a(T_a)] - \dot{n}_a[h_a(T_o) - T_o s_a(T_o)] \end{aligned} \quad (13)$$

The exergy rate of the stream of products of combustion at the adiabatic flame temperature is

$$\dot{E}x_b = \dot{n}_b(T_b)[h_b(T_b) - T_o s_b(T_b)] - \dot{n}_b(T_o)[h_b(T_o) - T_o s_b(T_o)] \quad (14)$$

where we must take into account that for stream "b" the chemical reactions are active and so the composition is a function of the temperature, and we use the fact that at standard conditions (T_o and p_o) the products of combustion have negligible exergy.

The entropy production by irreversibility in the burner is given by the entropy

balance

$$\dot{S}_{\text{irr}} = \dot{n}_b s_b - \dot{n}_a s_a \quad (15)$$

where s_a and s_b are the specific molar entropies of the inlet and outlet mixtures. For ideal gas mixture behavior,

$$\begin{aligned} \dot{S}_{\text{irr}} &= \dot{n}_b s_b - \dot{n}_a s_a \\ &= \sum_{i=1}^r \dot{n}_{ib} [s_{ii}(T_b, p_b) - s_{ii}(T_o, p_o)] - R \sum_{i=1}^r \dot{n}_{ib} \ln y_{ib} \\ &\quad - \sum_{i=1}^r \dot{n}_{ia} [s_{ii}(T_a, p_a) - s_{ii}(T_o, p_o)] + R \sum_{i=1}^r \dot{n}_{ia} \ln y_{ia} \\ &\quad + \sum_{i=1}^{\tau} \dot{\epsilon}_j (\Delta s^o)_j \end{aligned} \quad (16)$$

where the entropy of the j -th reaction at standard temperature and pressure

$$(\Delta s^o)_j = \sum_{i=1}^r \nu_i^{(j)} s_{ii}(T_o) = \sum_{i=1}^r \nu_i^{(j)} (\Delta s_f^o)_i \quad (17)$$

$(\Delta s_f^o)_i$ is the entropy of formation of the i -th constituent.

With respect to an environment at standard temperature T_o and pressure p_o , the entropy production due to irreversibility causes a rate of exergy destruction

$$\dot{E}x_{\text{destroyed}} = T_o \dot{S}_{\text{irr}} \quad (18)$$

Thus, the exergy rate of the stream of products of combustion at the adiabatic flame temperature is also given by

$$\dot{E}x_b = \dot{E}x_a - \dot{E}x_{\text{destroyed}} \quad (19)$$

The results may be shown graphically in a convenient way by defining the following dimensionless enthalpy, entropy and exergy

$$H = \frac{\dot{n}h - \dot{n}_b h_b(T_o)}{[-\dot{n}_{1a}(\Delta g^o)_1]} \quad (20)$$

$$S = \frac{\dot{n}s - \dot{n}_b s_b(T_o, p_o)}{[-\dot{n}_{1a}(\Delta g^o)_1]/T_o} \quad (21)$$

$$Ex = \dot{E}x / [-\dot{n}_{1a}(\Delta g^o)_1] \quad (22)$$

Figure 2 shows two curves on an H versus S graph. Curve “a” is that of the stable equilibrium states of a chemically inert mixture of methane, CH_4 , and the stoichiometric amount of air at pressure $p_a = p_o$, for temperatures T_a ranging from T_o ($= 298.15\text{K}$) to 1500K . Curve “b” is that of the chemical equilibrium states of the corresponding products of the combustion and dissociation reactions at pressure $p_a = p_o$, for temperatures T_b ranging from T_o to 3000K .

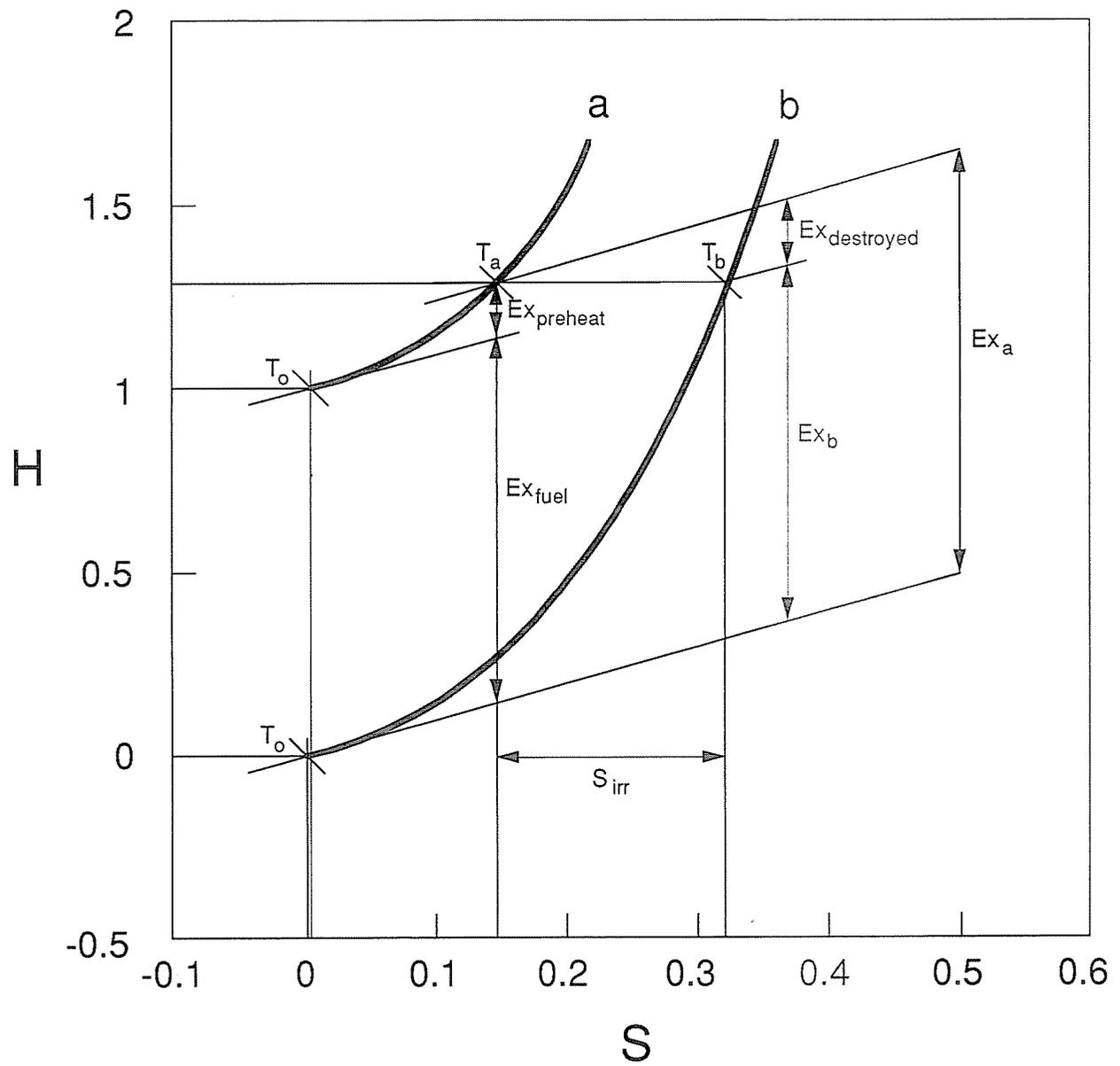


Figure 2.

It can be readily shown that on curve “*a*” the slope is equal to the ratio T_a/T_o and on curve “*b*” to the ratio T_b/T_o . So, on curve “*b*”, the point where the slope is equal to unity corresponds to the state of the products of combustion at temperature T_o . The line with unit slope tangent to that point is useful to visualize exergy values on the graph. Indeed, the vertical distance of a given point from that line can be readily shown to be equal to the value of Ex for the state represented by the given point. For example, the graph shows the state at T_o of the unburnt mixture (on curve “*a*”): the vertical distance of the corresponding point on the graph from the T_o line tangent to the “*b*” curve represents the normalized exergy of the unburnt mixture, Ex_{fuel} (equal to unity by virtue of the normalization chosen with Equation 22).

It is noteworthy that the vertical distance between the T_o point on the “*a*” curve and the T_o point on the “*b*” curve is equal to the ratio of the heating value ($-\Delta h^o$) of the fuel to its exergy value ($-\Delta g^o$). Similarly, the small horizontal distance between the two T_o points represents the ratio of the sum of the entropy of combustion (Δs^o) and the difference between the mixing entropies of the two mixtures multiplied by T_o to the Gibbs free energy of combustion or, equivalently, the ratio of the difference between exergy and heating values to the exergy value.

The state at T_a on curve “*a*” corresponds to $T_a = 1000\text{ K}$ of the stoichiometric methane-air mixture, and has exergy shown graphically by the vertical distance denoted by Ex_a ($=1.126$). The exergy required for preheating the unburnt mixture from T_o to T_a is shown graphically as the vertical distance denoted by Ex_{preheat} ($=0.126$). The point on curve “*b*” having the same value of H as that of the point at T_a on curve “*a*” represents the state of the products of combustion at the adiabatic flame temperature T_b ($= 2568\text{ K}$), defined by the energy balance, $H_b = H_a$ ($=1.258$). Correspondingly, the horizontal distance between the two points represents the normalized entropy production by irreversibility, $S_{\text{irr}} = S_b - S_a$ ($=0.316-0.132=0.184$). The graph shows also the corresponding vertical distance representing the exergy destroyed by irreversibility, $Ex_{\text{destroyed}}$ ($=0.184$). The products of combustion at T_b have identical energy content as the reactants at T_a but exergy Ex_b ($=0.942$) which is about 84% of the exergy of the preheated fuel-air mixture, $Ex_a = 1.126$.

We see clearly from the graph that the higher the preheating temperature the smaller S_{irr} and $Ex_{\text{destroyed}}$. However, lowering the entropy production by irreversibility S_{irr} by preheating is not sufficient because in addition to the entropy generation associated with the irreversibility of the flame, much additional entropy generation is associated with the heat transfer between the hot products of combustion and the working fluid flowing through the power plant devices. Such heat transfer is necessary because current technology materials, that must be used to contain and exploit the hot combustion products, cannot withstand temperatures much higher than 1400 K . Preheating lowers the irreversibility in the flame but increases the flame temperature and so the subsequent heat-transfer is across a larger temperature difference and hence more irreversible.

Therefore, in order to improve power plant efficiency, it is necessary not only to lower the flame irreversibility but also to lower the flame temperature, so as to reduce both the flame and the heat-transfer irreversibilities.

Dilution of the fuel-air mixture with an inert gas, such as nitrogen in atmospheric air, has the effect of reducing the flame temperature, but cannot reduce the overall

flame-and-heat-transfer irreversibility. Indeed, the process is equivalent to stoichiometric combustion in pure oxygen, with a high flame temperature, followed by heat transfer by mixing with the inert gas to reach a lower temperature T_b .

3. REVERSIBLE COMBUSTION

For hydrocarbon combustion flames under typical conditions the assumption of complete oxidation (as adopted in Section 2) is extremely accurate. Indeed, even if the adiabatic temperature T_b is a relatively high temperature (around 2300–3000 K), the equilibrium constant of the oxidation reaction (reaction 1, Equation 4) is extremely high and, therefore, practically no unburnt hydrocarbon is present in the products of combustion.

Nonetheless, we proceed by assuming a hypothetical fuel and a reaction mechanism that at a temperature T_b manageable by standard materials has a not-too-high equilibrium constant $K_1(T_b)$. In this case, we consider the H versus S diagram in Figure 3. Curve “ b ” represents the chemical equilibrium states of the products of the reaction. At the state at temperature T_b , we denote the composition by $n_b(T_b)$. Curve “ a ” represents the stable equilibrium states of a nonreacting mixture with fixed (“frozen”) composition $n_a = n_b(T_b)$, namely, the same composition as that of the state at T_b on curve “ b ”, but with all the reaction mechanisms “turned off”.

It can be shown[7] that curves “ a ” and “ b ” have a contact of first degree, i.e., are tangent, at the point at T_b . For any other value of the enthalpy H , the chemical equilibrium state has a higher entropy S , i.e., it is more stable than the fixed composition state of curve “ a ”.

It is now clear that starting with the mixture represented by the point at T_o on curve “ a ”, preheating it along curve “ a ” up to the temperature T_b while maintaining all reactions inactive, then activating the reactions and cooling down the chemically active mixture to T_o along curve “ b ” achieves completion of the reaction without passing through an irreversible flame.

4. AN EXAMPLE

In principle, a reversible flame can be obtained at any temperature and pressure provided the chemical kinetics can be controlled.

As an example, we consider a simplified model of the oxidation of hydrogen in pure oxygen according to the single reaction



with the equilibrium constant approximated by the relation

$$K(T) = \exp\left(-6.866 + \frac{29911}{T}\right) \quad (24)$$

so that at the chemical equilibrium state at temperature T_b and pressure p_b the mole fractions satisfy the equation

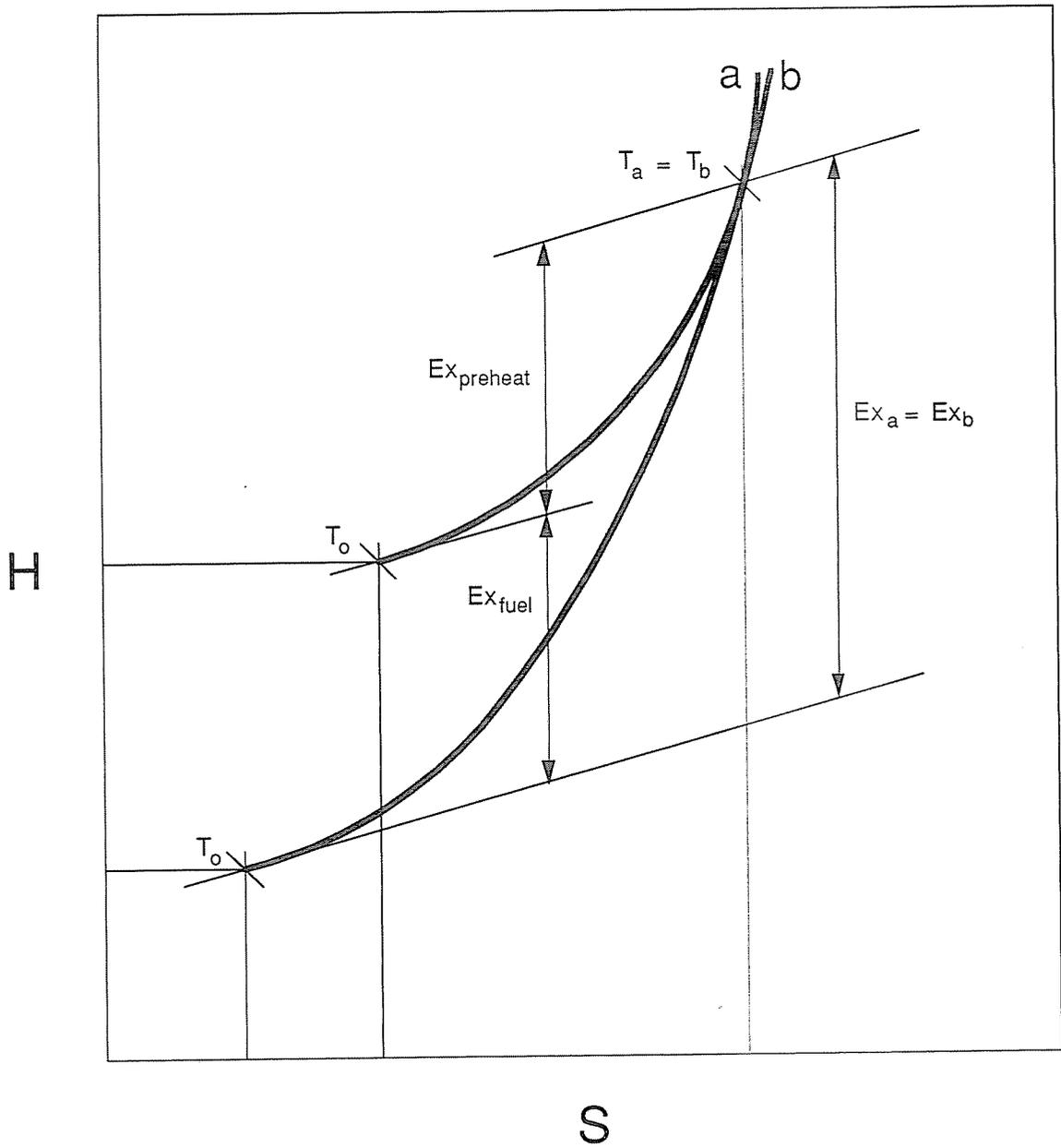


Figure 3.

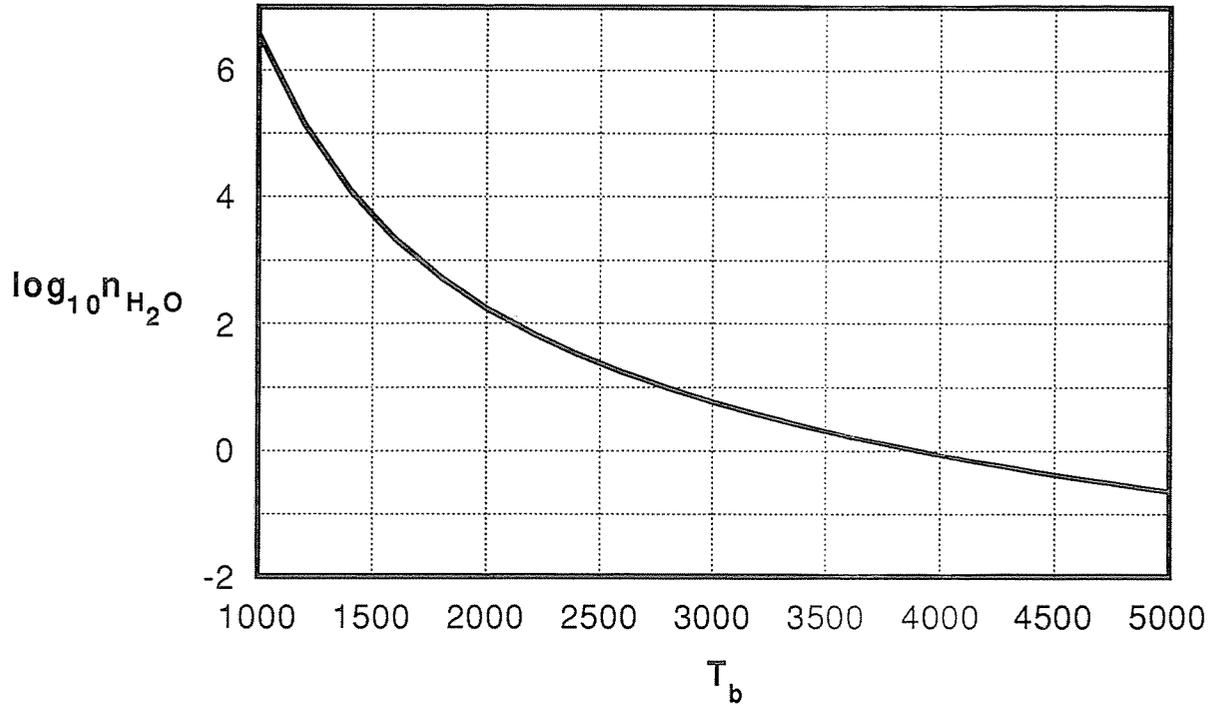


Figure 4.

$$\frac{y_{\text{H}_2\text{O}}}{y_{\text{H}_2}(y_{\text{O}_2})^{1/2}} = \left(\frac{p_o}{p_b}\right)^{-1/2} K(T_b) \quad (25)$$

For example, if H_2 , O_2 and H_2O are the only constituents, then Equation 25 becomes

$$\frac{n_{\text{H}_2\text{O}}(n_{\text{H}_2} + n_{\text{O}_2} + n_{\text{H}_2\text{O}})^{1/2}}{n_{\text{H}_2}(n_{\text{O}_2})^{1/2}} = \left(\frac{p_o}{p_b}\right)^{-1/2} K(T_b) \quad (26)$$

For $n_{\text{H}_2} = 1 \text{ mol}$, $n_{\text{O}_2} = 1/2 \text{ mol}$ and $p_b = p_o$ we find

$$n_{\text{H}_2\text{O}} \left(\frac{3}{2} + n_{\text{H}_2\text{O}}\right)^{1/2} = \left(\frac{1}{2}\right)^{-1/2} \exp\left(-6.866 + \frac{29911}{T_b}\right) \quad (27)$$

and the resulting relation between $n_{\text{H}_2\text{O}}$ and T_b is plotted in Figure 6. In particular, for $T_b = 1600 \text{ K}$, 1800 K , 2000 K , 2200 K , 2400 K , and 2600 K , respectively, $n_{\text{H}_2\text{O}} = 2110 \text{ mol}$, 528 mol , 174 mol , 70 mol , 32 mol , and 17 mol .

Figure 5 shows H versus S graphs corresponding to $n_{\text{H}_2\text{O}} = 23.5 \text{ mol}$ and $T_b = 2497 \text{ K}$. Curve "a" represents the states of the "frozen composition" mixture of $n_{\text{H}_2} = 1 \text{ mol}$, $n_{\text{O}_2} = 1/2 \text{ mol}$, and $n_{\text{H}_2\text{O}} = 23.5 \text{ mol}$; curve "a'" represents the overall enthalpy and entropy of three separate "frozen composition" single-constituent streams with the same given amounts. It is noteworthy that the entropy production by irreversibility due to mixing the three streams is about 0.07, i.e., mixing destroys 7% of the fuel exergy, a nonnegligible amount which increases for larger dilution of the fuel, i.e., for larger values of $n_{\text{H}_2\text{O}}$ in our example. Curve "b" represents the chemical equilibrium states.

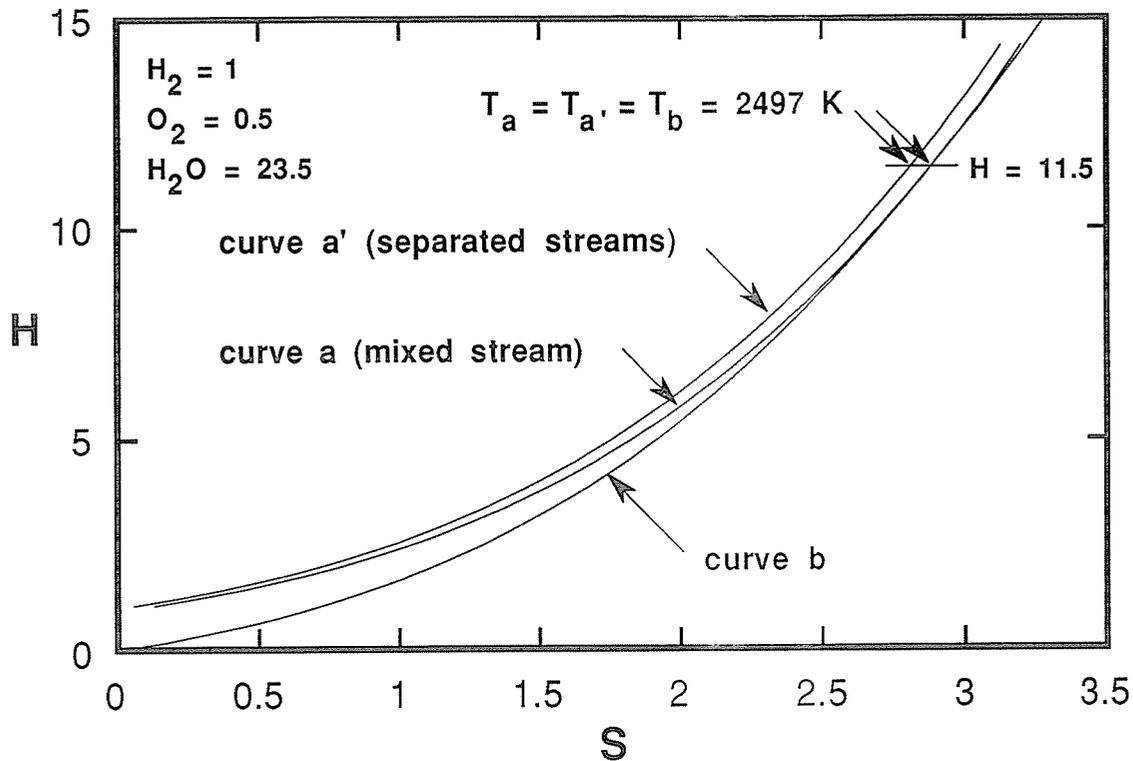


Figure 5.

Figure 6 shows T versus H graphs corresponding to the curves “a” and “b” in Figure 5. The two graphs cross at $T_a = T_b = 2497\text{ K}$ and $H = 11.5$. At each value of H , T_b is higher than T_a of as much as 150 K . The fuel exergy can be fully extracted only by exploiting this temperature difference with reversible machinery. The practical way of doing so in such a way as to minimize irreversibilities remains to be investigated. It is clear that just using stream “b” to preheat directly stream “a”, from the point of view of irreversibility, is entirely equivalent to just burning the mixture without preheating.

CONCLUSIONS

A practical implementation of the method just cited requires to overcome several difficulties. First we need to identify a suitable chemical reaction mechanism or scheme, with a not-too-high equilibrium constant at a not-too-high temperature T_b so that in the “a” stream the fuel is not so extremely diluted as it would be if the scheme is applied to the oxidation of a standard hydrocarbon. Then, we need to identify means to inhibit the chemical reactions in stream “a” while preheating from T_o to T_b . To this end it may help somehow to substitute the mixture in stream “a” with several separated streams each with a single constituent, thus, at least, the only reactions that must be inhibited are the dissociation reactions. Of course, before or after preheating, the streams are to be mixed, and this causes some entropy production by irreversibility which may not be negligible with respect to the entropy production in a standard hydrocarbon combustion flame if the fuel is too diluted in the reactants.

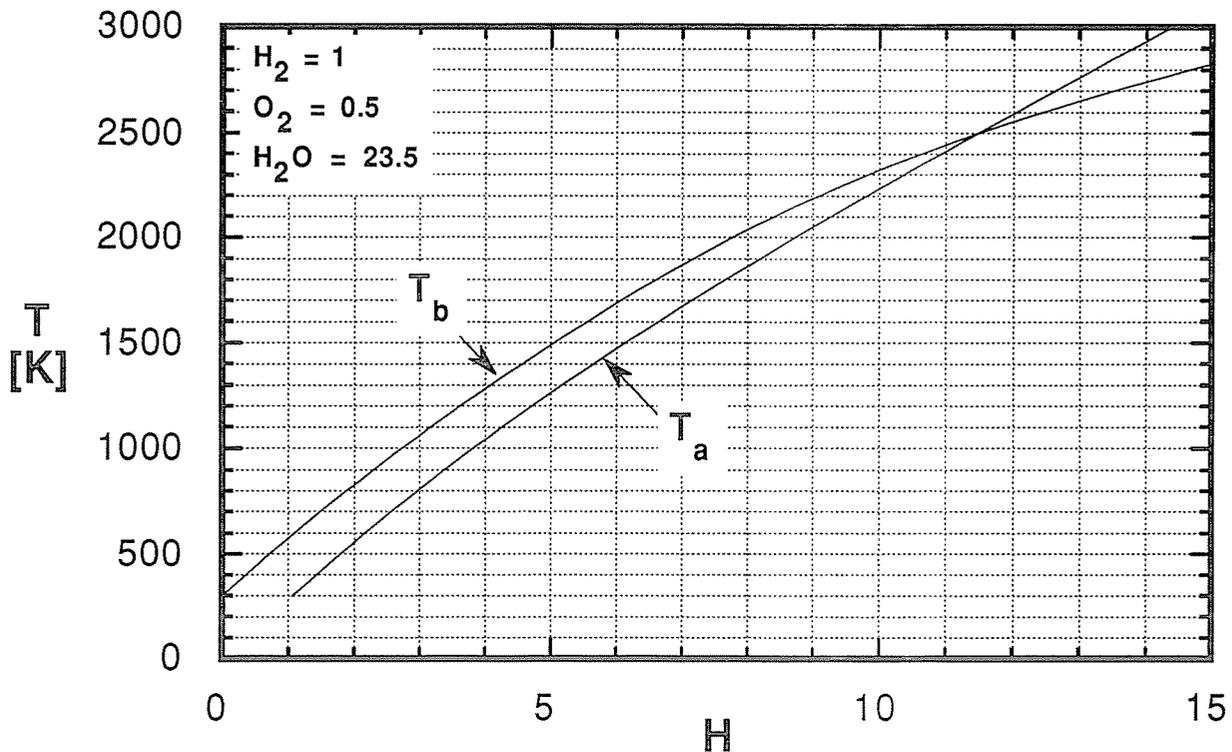


Figure 6.

We conclude that the concept of reversible combustion is worth further investigation and development, particularly on the chemical kinetics of reactant dissociation and on the most suitable machinery and working-fluid cycle that could make it practically feasible.

REFERENCES

1. J.H. Keenan, *Thermodynamics*, Wiley, New York, 1941, Chapter 16, p. 269.
2. E.F. Obert, *Thermodynamics*, McGraw-Hill, 1948, p. 459. E.F. Obert, *Internal Combustion Engines and Air Pollution*, Harper and Row, New York, 1973, p. 84.
3. H.J. Richter and K.F. Knoche, "Reversibility of Combustion Processes," in *Efficiency and Costing. Second Law Analysis of Processes*, R.A. Gaggioli, Editor, Am.Chem.Soc. Symposium Series, Vol. 235, p.71 (1983).
4. F.J. Weinberg, "The First Half-Million Years of Combustion Research and Today's Burning Problems", *Prog. Energy Combust. Sci.*, Vol. 1, 17 (1975) and references therein. See also F.J. Weinberg, "Combustion Temperature: the Future?", *Nature*, Vol. 233, 239 (1971).
5. E.P. Gyftopoulos and G.P. Beretta, *Thermodynamics: Foundations and Applications*, Macmillan, New York, 1991, Chapters 29-31.
6. E.P. Gyftopoulos and G.P. Beretta, *op.cit.*, Section 29.9.
7. E.P. Gyftopoulos and G.P. Beretta, *op.cit.*, Section 30.7.