

REMARKS OF "COMBUSTION THEORY"

by

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I find myself in a somewhat peculiar situation. I am speaking to you as a member of a session devoted to the nuts and bolts problems of operating real incinerator systems on a day-to-day basis. The title of the talk provided to me was "Combustion Theory" and I have been directed to contain my remarks to a ten minute period. Even if I felt qualified to present Combustion Theory, it would be impossible in the ten minutes that is available. Whole books have been written and people have devoted a major part of their lives to development of Combustion Theory. I am not one of these. For this reason, I take a somewhat detached view of Combustion Theory. On the other hand, I am not uninvolved with the day-by-day operations of combustion systems, and can take a rather detached view of the nuts and bolts day-to-day problems. From this somewhat remote position, I am able to see some of the problems of the practitioner as well as some of the theories of the theoretician. If my perception is right, I can see very little communication between these two groups. The theory is not being used in practice and the practical problems are not being considered by the theoreticians.

Much of the problems may be that of communications or the desire to even communicate. One reason that I would like to propose for this communication gap is a lack of a common language. Several languages and several dialects are being spoken and each group is comfortable only with its particular language. It is my purpose to try to act as an interpreter and to perform the necessary translation so that the communication can be increased. I hope to do this with two or three examples.

Before presenting these examples, I would like to ask two questions regarding a relationship between theory and practice.

Question 1: What does theory have to offer the practitioner?

--There are two areas where the theory should help in the practice of incineration. The first is diagnostic. If one is encountering difficulties with an incinerator, theory should be able to suggest what is occurring and what steps can be made toward remedying the situation. The second use of theory would be to suggest changes that might be made in future operations. It would point a direction that one would look to for future improvements.

Question 2: How could the practitioner help the theorist?

--Theory should explain what is occurring in the real world. The practitioner should be able to point out where a theory does not explain what is actually occurring and to point out observations that need to be explained by some unified theory.

The purpose of mathematical models should be to provide a mathematical representation of the actual physical phenomena. If the model is a good representation of the physical situation, then it is a valuable tool to diagnose real problems as well as suggest the cure for problems that arise. A model that is unable to explain or incorrectly interpret the physical phenomena is deficient and must be discarded or modified.

With your permission, I would like now to turn to the post of interpreter. Figure 1 shows two boxes. Each contains a different material that can be burned. We would like to consider which of these materials would most easily be burned in an incinerator. To help in this evaluation the chemical analysis is provided. This is shown on the face of each box in Figure 1. From this analysis, what can be said about the combustion characteristics? Not a great deal, really. We can now add to this list of information, the heating value of what is in the box. We are still unable to tell how it will burn in an incinerator. To appreciate this, it might be useful to reveal what is in the two boxes. This is shown in Figure 2. Box A contains small pieces of wood about the size of a matchstick. Box B contains one single chunk of anthracite coal. If I put a match to the woodsticks they would readily ignite and burn rather rapidly. On the other hand, if I put a match to the anthracite coal, there would be almost no effect whatsoever. It should be clear, therefore, that by obtaining the chemical analysis and the heating value did not reveal to us the burning characteristics of the material. A proximate analysis of these two materials would have been somewhat more revealing, but not sufficiently revealing to adequately characterize the materials with respect to their combustion characteristics.

The previous speaker has shown a plot of the time it takes for materials of various sizes to burn at various temperatures. These were interpreted in terms of activation energy, Arrhenius law, reactivity, etc. The reactivity is a measure of how easily a material burns. Wood is much more reactive than is anthracite coal (it burns easier). The activation energy is an indication of how fast the reaction rate increases with an increase in temperature (burns faster when hot). Typically, for

most chemical reactions an increase of 5.6 to 11 degrees K (10 to 20 degrees F) will result in a doubling of the reaction rate. Thus, once we get the anthracite coal up to a significantly high temperature the reaction rate becomes fast enough to sustain the temperature and the anthracite will continue to burn. If one would have prior knowledge of the reactivity, and the activation energy, then one has a far better characterization of the fuel in terms of how it will react (combust) in the reactor than by knowing the chemical analysis. These values are not known for most materials that are to be incinerated, thus prior characterization of the feed with respect to combustion characteristics is not possible. This discussion suggests the types of measurements we should be making in order to obtain proper fuel combustion characteristics. It provides direction toward future efforts. This is a positive role for theory that will directly help the practitioner.

The Arrhenius Law predicts that the reaction rate would increase with an increase in temperature. This increased rate is well-known, well-documented and consistent with the theory. Again theory and practice agree.

Figure 3 is a plot of the burn-out of anthracite dust in various combustor systems. The difference between the various systems is the mixing patterns within the combustion unit. The curve labeled the completely stirred tank system is shown by curve A. Such a system is represented by system A in Figure 4. The fuel entering the combustion system is completely mixed with the contents of the system as in Figure 4A. The material leaving the system has equal probability of being a particle that has just entered the system as one that has resided in the system for a period of time. Therefore, if a system is completely mixed, some of the material is swept out of the reactor before it has had sufficient time to react. Thus, curve A of Figure 3 suggests that a large fraction of unburned material will leave the combustion unit. In contrast to the completely stirred tank reactor, is what is called a plug-flow reactor. In this system the particles move as waves through the combustor and each fuel particle would remain in the reactor a fixed period of time. The time that a particle resides in the system is that which gives rise to particle "age". All particles leave a plug-flow combustor with the same age. The carbon burn-out for a plug flow reactor is shown in curve B of Figure 3. Curve C Figure 3 provides burn-out for a system that provides for the complete burn-out of the fuel for the shortest residence time in the reactor system. For this system, the heat release rate for complete combustion would be significantly larger than either the plug-flow reactor or the completely stirred tank reactor. This is accomplished by providing for complete mixing section at the beginning of the reaction zone followed by a section that is in plug or wave flow. This theory would suggest that turbulence (which causes mixing) is important but should be provided just above the burning bed (but not over the whole incinerator). This gives some suggestion as to where and how the air jets causing turbulence should be located. It is consistent with practice.

From the point of view of the rates or reaction, an increase in temperature is desirable. This agrees with the efforts to raise the temperature to achieve better incineration. Theory tells us this is only

true up to a point. Thermodynamics shows that as the temperature is increased for a reaction that gives off heat, that the equilibrium composition always shifts toward the products of incomplete combustion. This is emphasized in Figure 5. The curve labeled "Chemical Equilibrium" presents the amount of conversion that would take place as a given temperature at equilibrium. The curve labeled actual conversion is the conversion that would actually be achieved for fuels remaining in the reactor a given period of time.

Figure 5 shows that at low temperature the equilibrium conversion favors complete conversion. However, the reaction rate at low temperatures is so slow that almost no reaction occurs. This reaction rate may be increased by increasing the temperature. This can be seen on Figure 5. This favorable trend does not continue because the chemical equilibrium begins to shift toward incomplete reaction. Figure 5 shows at higher temperatures lower conversions are achieved. The correct way to express the result of increasing temperature is "increasing temperature results in the chemical reaction moving more rapidly to its equilibrium condition." Thus, extremely high temperatures provide products of incomplete reaction.

How does this apply to incineration? For combustion systems the chemical equilibrium conversion does not show a significant decrease until temperatures above 1922 degrees K (3000 degrees F) are achieved. No temperature recorder placed in the incinerator would be expected to record such high temperatures. The temperatures recorded are mixed mean temperatures and do not represent the temperatures of "hot spots" in the incinerator. If one can see either light red or white radiation then one is rather assured that there are areas where high temperatures are being achieved and that the chemical equilibrium constraint begins to become significant. If we have such areas, the chemical equilibrium will move away from CO_2 and H_2O and toward the formation of the CO and hydrogen. If, as the gases leave these hot zones are quenched rapidly to low temperatures then the CO and hydrogen will be retained even though there is significant amounts of excess air. By quenching the gas very rapidly, the equilibrium condition moves toward complete combustion (CO_2 and water) but the rate of reaction which becomes insignificant. Such explanation may account for observing quantities of CO and hydrogen even though significant excess air is being utilized. It suggests that rapid quenching of gases over a very hot zone would lead to quantities of unburned gases. Does this explain some observations made in incinerators? Are these predictions from theory useful?

I hope these examples show where theory may be helpful in day-to-day operations. Are there more examples? Most assuredly if the theoretician and practitioner increase their level of communication and begin to look toward each other for assistance. I thank you for your time and patience and hope that my remarks serve some useful role toward more cooperation and understanding.

Figure 1

Fuels - Chemical Analysis

A	B
C = 52.6%	C = 86.7%
H = 7.0%	H = 2.2%
O = 40.1%	O = 2.9%
S = --	S = 0.5%
H.V. = 9,610	H.V. = 13,860

Conversion Factor: 1(Btu) = 1.055 (kJ)

Figure 2

Fuels - Chemical Reactivity

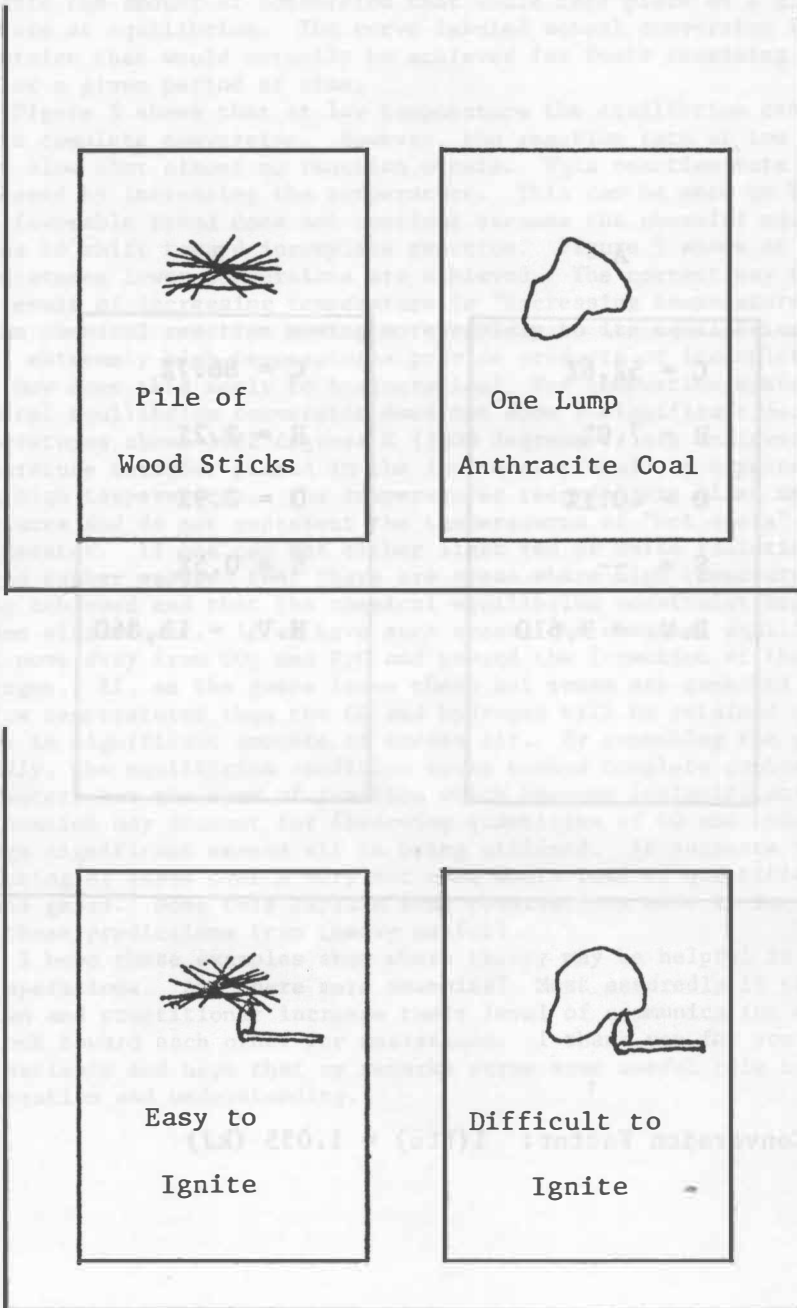


Figure 3

Fuel Burnout Times

1. Plug Flow
2. Complete Mixing
3. Complete Mixing followed by Plug Flow

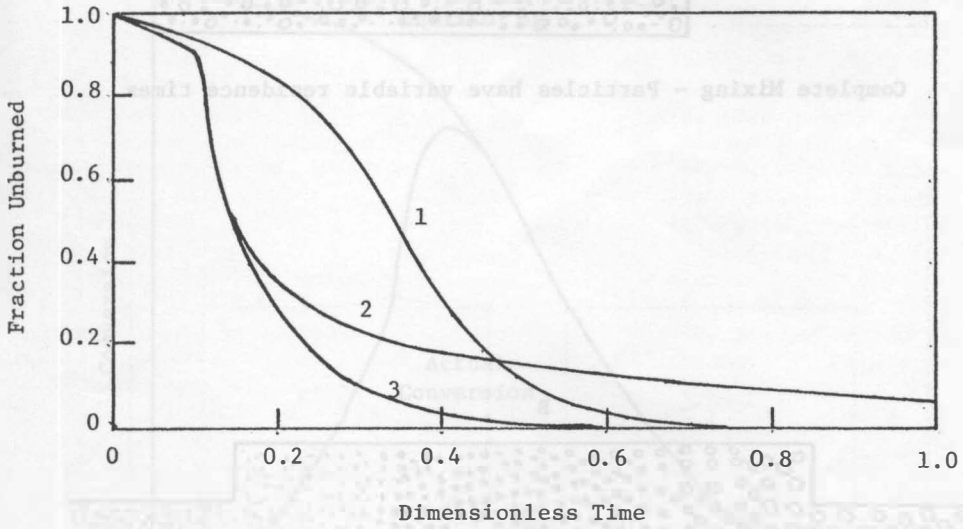
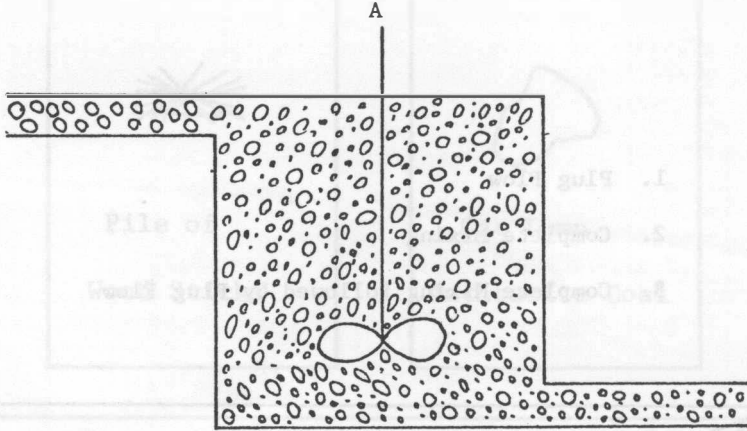
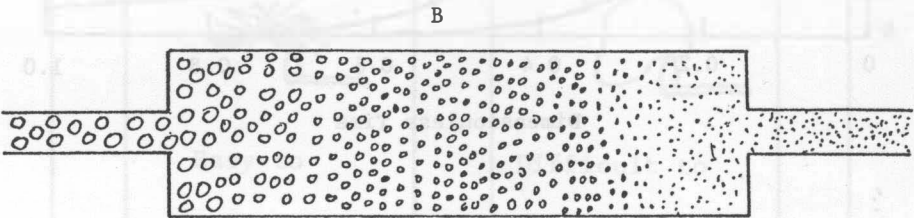


Figure 4

Reactor Flow Systems



Complete Mixing - Particles have variable residence times.



Plug Flow - All particles have same residence time.

Figure 5

Fuel Conversion versus Temperature

