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Temperatures in flames and fires

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Introduction

It is unfortunately not too rare to find that fire investigators estimate flame temperatures by looking up a handbook value, which turns out to the *adiabatic flame temperature*. Statements are then made about whether some materials could have melted, softened, lost strength, etc., based on comparing such a flame temperature against the material's melting point, etc. The purpose of this short paper is to point out the fallacies of doing this, and to present some more appropriate information for a more realistic assessment.

First, we must point out that measuring of flame temperatures to a high degree of precision is quite difficult, and many combustion research scientists have devoted decades to studying the task. The difficulties come from two sources: (1) intrusiveness of instrumentation; and (2) interpretation difficulties due to the time-varying nature of the measurement. Non-intrusive (e.g., optical laser techniques) methods are available, but these are difficult and expensive to make and are generally not applied to the study of building fires. In most cases, thermocouples are used for temperature measurement. These have a multitude of potential errors, including surface reactions, radiation, stem loss, etc. A whole textbook is available on the subject of instrumentation for studying flames [1]. As we see below, the flames of most interest for unwanted fires are turbulent. This time fluctuation presents tremendous difficulties in making measurements and in interpreting them meaningfully. Such flames move about in little "packets." Thus, a measurement at a single location returns a complicated average value of reacting and unreacting packets flowing by. Some of these issues are elucidated in [2].

Even careful laboratory reconstructions of fires cannot bring in the kind of painstaking temperature measuring technologies which are used by combustion scientists doing fundamental research studies. Thus, it must be kept in mind that fire temperatures, when applied to the context of measurement of building fires, may be quite imprecise, and their errors not well characterized.

Flame types

Before we discuss details of flame temperatures, it is important to distinguish between some of the major flame types. Flames can be divided into 4 categories:

- laminar, premixed
- laminar, diffusion
- turbulent, premixed
- turbulent, diffusion

An example of a laminar premixed flame is a Bunsen burner flame. Laminar means that the flow streamlines are smooth and do not bounce around significantly. Two photos taken a few seconds apart will show nearly identical images. Premixed means that the fuel and the oxidizer are mixed before the combustion zone occurs.

A laminar diffusion flame is a candle. The fuel comes from the wax vapor, while the oxidizer is air; they do not mix before being introduced (by *diffusion*) into the flame zone. A peak temperature of around 1400°C is found in a candle flame [3].

Most turbulent premixed flames are from engineered combustion systems: boilers, furnaces, etc. In such systems, the air and the fuel are premixed in some burner device. Since the flames are turbulent, two sequential photos would show a greatly different flame shape and location.

Most unwanted fires fall into the category of turbulent diffusion flames. Since no burner or other mechanical device exists for mixing fuel and air, the flames are diffusion type.

Adiabatic flame temperature

When one consults combustion textbooks for the topic of 'flame temperature,' what one normally finds are tabulations of the *adiabatic flame temperature*. 'Adiabatic' means without losing heat. Thus, these temperatures would be achieved in a (fictional) combustion system where there were no losses. Even though real-world combustion systems are not adiabatic, the reason why such tabulations are convenient is because these temperatures can be computed from fundamental thermochemical considerations: a fire experiment is not necessary. For methane burning in air, the adiabatic flame temperature is 1949°C, while for propane it is 1977°C, for example. The value for wood is nearly identical to that for propane. The adiabatic flame temperatures for most common organic substances burned in air are, in fact, nearly indistinguishable. These temperatures are vastly higher than what any thermocouple inserted into a building fire will register!

Flames temperatures of open flames

For convenience, we can subdivide the turbulent diffusion flames from unwanted fires into two types: flames in the open, and room fires. First we will consider open flames.

The starting point for discussing this topic can be the work of the late Dr. McCaffrey, who made extensive measurements [4] of temperatures in turbulent diffusion flames. He used gas burners in a "pool fire" mode (i.e., non-premixed) and studied various characteristics of such fire plumes. He described three different regimes in such a fire plume:

1. Slightly above the base of the fire begins the *continuous flame* region. Here the temperatures are constant and are slightly below 900°C.
2. Above the solid flame region is the *intermittent flame* region. Here the temperatures are continuously dropping as one moves up the plume. The visible flame tips correspond to a temperature of about 320°C.
3. Finally, beyond the flame tips is the thermal plume region, where no more flames are visible and temperature continually drop with height.

French researchers at the University of Poitiers recently made the same types of measurements and reported numerical values [5] indistinguishable from McCaffrey's. Cox and Chitty [6] measured similar plumes and obtained very similar results: a temperature of 900°C in the continuous flame region, and a temperature of around 340°C at the flame tips. The latter value does not appear to be a universal constant. Cox and Chitty later measured slightly higher heat release rate fires, and found a flame tip temperature of around 550°C. In a later paper [7], researchers from the same laboratory examined turbulent diffusion flames under slightly different conditions, and found peak values of 1150-1250°C for natural gas flames, which is rather higher than 900°C. The above results were from fires of circular or square fuel shape. Yuan and Cox [8] measured line-source type fires. They found a temperature of 898°C in the continuous flame region, and a flame tip temperature of around 340°C. This suggests that such results are not dependent on the shape of the fuel source.

In studying fires in a warehouse storage rack geometry, Ingason [9] found an average solid-flame temperature of 870°C. At the visible flame tips, the average temperature was 450°C, but the range was large, covering 300~600°C. In a related study, Ingason and de Ris [10] found typical flame tip temperatures of 400°C for burner flames of propane, propylene, and carbon monoxide fuels.

Sullivan et al. [14] cite Australian studies on wildfire flames, finding that flame tip temperature corresponds to 300°C, while peak values around 927°C can be expected.

Heskestad [11] adopts a criterion of 500°C *rise* as defining the flame tip temperature, i.e. an actual temperature of about 520°C.

Taking all of the above information in account, it appears that flame tip temperatures for turbulent diffusion flames should be estimated as being around 320~400°C. For small flames (less than about 1 m base diameter), continuous flame region temperatures of around 900°C should be expected. For large pools, the latter value can rise to 1100~1200°C.

Flame temperatures in room fires

There is fairly broad agreement in the fire science community that flashover is reached when the average upper gas temperature in the room exceeds about 600°C. Prior to that point, no generalizations should be made: There will be zones of 900°C flame temperatures, but wide spatial variations will be seen. Of interest, however, is the peak fire temperature normally associated with room fires. The peak value is governed by ventilation and fuel supply characteristics [12] and so such values will form a wide frequency distribution. Of interest is the maximum value which is fairly regularly found. This value turns out to be around 1200°C, although a typical post-flashover room fire will more commonly be 900~1000°C. The time-temperature curve for the standard fire endurance test, ASTM E 119 [13] goes up to 1260°C, but this is reached only in 8 hr. In actual fact, no jurisdiction demands fire endurance periods for over 4 hr, at which point the curve only reaches 1093°C.

The peak expected temperatures in room fires, then, are slightly greater than those found in free-burning fire plumes. This is to be expected. The amount that the fire plume's temperature drops below the adiabatic flame temperature is determined by the heat losses from the flame. When a flame is far away from any walls and does not heat up the enclosure, it radiates to surroundings which are essentially at 20°C. If the flame is big enough (or the room small enough) for the room walls to heat up substantially, then the flame exchanges radiation with a body that is several hundred °C; the consequence is smaller heat losses, and, therefore, a higher flame temperature.

Temperatures of objects

It is common to find that investigators assume that an object next to a flame of a certain temperature will also be of that same temperature. This is, of course, untrue. If a flame is exchanging heat with a object which was initially at room temperature, it will take a finite amount of time for that object to rise to a temperature which is 'close' to that of the flame. Exactly how long it will take for it to rise to a certain value is the subject for the study of *heat transfer*. Heat transfer is usually presented to engineering students over several semesters of university classes, so it should be clear that simple rules-of-thumb would not be expected. Here, we will merely point out that the rate at which target objects heat up is largely governed by their thermal conductivity, density, and size. Small, low-density, low-conductivity objects will heat up much faster than massive, heavy-weight ones.

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Return to Home Page

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