

## Plasma and Flames – The Burning Question

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### *Do flames contain plasma?*

Phrased one way or another, this is a frequently asked question.

**The Short Answer:** Some do; some don't.

**The Medium Answer:** Whether a plasma exists in a flame depends on the material being burned and the temperature. The temperature in a flame varies greatly from one region to another. Depending on the material being burned, the temperature can range from a few hundred degrees Celcius in one region to thousands of degrees elsewhere. Furthermore, the nature of the burning material and the temperatures at different locations within a flame determine the kinds of atoms and molecules that are present.

In a cool gas, the atoms are generally electrically neutral; each atom has a positively charged nucleus surrounded by a number of negatively charged electrons that exactly balance the positive charge. But if the gas temperature is high enough, particle collisions can remove some electrons from atoms, resulting in a mixture of freely moving electrons and the atoms from which they were stripped. Those atoms, which are left with an excess positive charge, are called "ions," and those particles as well as the gas are said to be "ionized." All regions of a flame will contain at least some charged particles and, therefore, will be ionized. The types of atoms and molecules present and their temperature determine how many of them become ionized. But does this ionization within the flame constitute a plasma?



**A natural gas stove flame.**

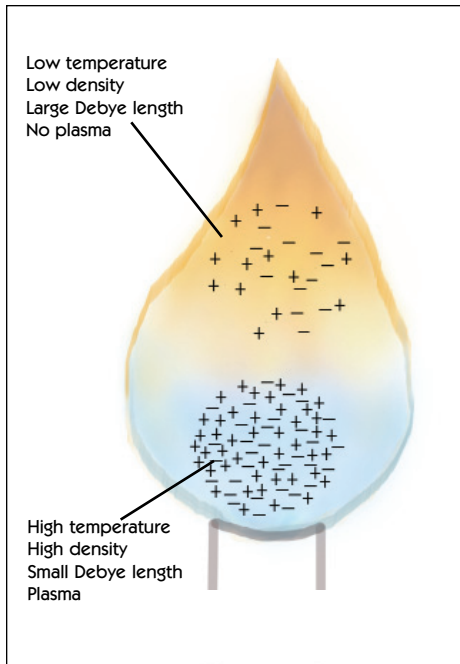
A plasma is an ionized gas. However, not all ionized gases are plasmas. In order for an ionized region of a flame to be plasma, it must contain enough charged particles for that region to exhibit unique electrical properties of plasma, which are distinctly different from properties of other states of matter. This leads to . . .

**The Long Answer:** To be plasma, a region must contain enough negative and positive charged particles for them to interact with each other in groups, rather than individually as they do in very weakly-ionized gases. Effects that result from collections of charged particles interacting with each other are called "collective effects." Thus, the key criterion for an ionized gas to be a plasma is that there are enough charged particles to exhibit collective effects.

There are many kinds of collective effects. The most important one for defining a plasma is the generation of internal electric fields that oppose and cancel externally-applied fields. That is, plasmas can shield themselves from externally-applied electric fields.

Say there is a collection of positive and negative charges in a gas, and an electric field is applied to the group. The positive charges will be pushed by that field in one direction and the negative charges in the opposite direction. But as the two charged groups separate, they will themselves produce an electric field between them that is in the opposite direction from the applied field. If there are enough charged particles, small charge separations can create internal electric fields that are large enough to totally cancel out the applied field between them. The externally-applied field is then prevented from fully penetrating into the collection of charged particles. If a collection of charged particles can shield itself from externally-applied fields in this way, it is a plasma.

The distance that an externally-applied electric field can penetrate into a collection of charged particles is called the "Debye length" (named after the Dutch scientist Peter J. W. Debye, 1884-1966). The Debye length becomes smaller as



**If a flame contains plasma, the plasma would be located where the charged-particle density is high enough for the Debye length to be small compared with the size of the high-density region.**

the density of charged particles increases. To restate the main criterion for an ionized gas to be a plasma: A group of charged particles is a plasma if the Debye length is smaller than the group's smallest dimension. Thus, when the Debye length is much smaller than a flame, that flame very likely contains plasma. (A technical point: For the idea of Debye length to be meaningful, there must be a relatively large number of charged particles in a volume of a sphere with radius equal to the Debye length.)

Since the density of charged particles increases as temperature increases, a high-temperature region in a flame may contain enough charged particles to be a plasma. Lower-temperature flames contain no significantly ionized regions and no plasma.

An example of a flame with relatively low temperatures is the flame of a household wax candle. The maximum temperature is less than 1,500 degrees Celsius, too low for much ionization to occur. However, some flames are much hotter than that. For example, in some burning mixtures of acetylene (made up of hydrogen and carbon) and oxygen, at a pressure of one atmosphere, the peak temperature in a flame has been measured to exceed 3,100 degrees Celsius. Calculations for a particular mixture of those gases indicate an electron density high enough for the Debye length to be only about 0.01 millimeters. (The calculated density satisfies the requirement that there are many charged particles in a spherical volume with radius equal to the Debye length.) Since the Debye length is much smaller than a flame, such a flame would be expected to contain plasma.

**The Future Answer:** At present, little detailed information is available for determining if a flame contains plasma. What we need are measurements and/or mathematical calculations of charged particle densities at specific locations in a flame. Since flame properties vary greatly from one region to another, considerable effort is required to obtain the needed data.

In some cases, charged particle densities can be calculated from measured temperatures. Temperatures in some flames have been measured accurately, but not in the detail required for determining plasma properties in particular regions. Although temperatures in some flames can be estimated by their color, that method is far from reliable. Indeed, some flames do not produce much visible light at all. For example, a pure hydrogen flame is nearly invisible. (This is a concern for hydrogen leaks at oil refineries, and will be for filling stations in a future hydrogen economy.)

Detailed mathematical calculations of temperatures and charged-particle densities in small regions of a flame are complex, since many processes are at work. Those calculations involve chemical processes, gas dynamics, heat transfer, and the production of visible and non-visible light -- all in a gas with strongly varying properties.

Historically, long before the word "plasma" was conceived and first published in 1928, experiments were carried out on electrical properties of flames. Technical journal articles can be found extending back to the early 1800s. However, although flames have been studied for a long time, we still have a long way to go to understand them in the detail required to establish the presence or absence of plasma.

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**For more information: Call Toll Free 1-877-PLASMAS (752-7627) • E-mail: CPS@plasmacoalition.org  
Visit our website at <http://www.plasmacoalition.org>**