



by Dr. Mahesh Panchagnula

We have heard this often, especially the recent barrage of lawsuits against tobacco companies. But do we have to worry about such regulations in our industry? In past years, smoke has caused some to get the misconception that oil heat is environmentally unfriendly. This has changed considerably, however, with recent advances in burner designs. As a result of these advances, particulate emissions from oilburners have decreased by a factor of 10 over the last thirty years.

The environmental regulations for smoke have become stricter. The U.S. EPA has published guidelines that all oilheat appliances should operate at a smoke number of 1 or less. This restriction is even more stringent in Europe. For example, in Germany all oilheat appliances that are 400,000 btuh and under in capacity must operate at smoke numbers less than or at 0.5.

Therefore, a continuous effort to further reduce particulate emissions by understanding the mechanism of smoke formation and implementing design changes becomes necessary. Let us now look into certain aspects of spray combustion and smoke formation processes.

### **SPRAY COMBUSTION**

Oilburners use a combusting spray to generate heat. The use of liquid fuel spray combustion commenced over a century ago when it was discovered that the atomization of fuel oils provided a convenient means of obtaining self-sustaining flames.

The spray produced by the nozzle consists of a number of drops, varying in size, that are suspended in a stream of air. The droplets evaporate and act as sources of fuel vapor. The fuel vapor burns with the surrounding oxidant (which is usually air) as a diffusion flame around the droplet. A diffusion flame is one where the fuel vapor that is generated by the droplet evaporation process has to diffuse and mix with the oxygen in the air before combustion can be initiated. Often, this process is controlled by

the rate of vapor diffusion and hence the term "diffusion flame." This is the most prevalent form of combustion in domestic and some commercial oil heating appliances.

The other form involves initial evaporation of the lighter components of the oil followed by liquid cracking of the higher fractions of the oil to carbon (or coke). The carbon thus formed subsequently burns out under the high temperature conditions in the combustor to complete the combustion reaction. This form of combustion generally occurs in some mid to large-scale burners especially in ones that fire heavier oils.

The way the fuel spray and the combustion air are mixed is crucial in determining how the overall combustion proceeds. If the fuel spray is initially well mixed with the combustion air, two cases of combustion can be identified. These are "heterogeneous" combustion and "homogenous" combustion.

In the former case, the droplets burn either as individual droplets each with a surrounding flame or as droplets in a sea of flame, but in either event the system is essentially heterogeneous in that both liquid oil and fuel vapor are present in the flame zone. This is the form of combustion that is predominant in most oil heating applications and is referred to as homogenous combustion.

In homogenous spray combustion, the droplets evaporate prior to their arrival in the flame zone and the flame front is supported essentially by fuel vapor and air. This form of combustion can be observed in some "blue flame burners." Homogenous combustion is favored in systems containing small droplets, particularly of volatile fuels.

In real systems, a wide range of droplet sizes and fuel components are involved and both homogenous and heterogeneous modes of combustion can occur simultaneously. This is frequently advantageous.

Since the combustion of sprays mainly involves the gas phase reaction of fuel vapor with air, the predominant pollutants, namely

\*Design Engineer  
Delavan Inc., Bamberg, SC  
803-245-4347

carbon monoxide, SO<sub>x</sub>, NO<sub>x</sub>, unburned hydrocarbons and smoke, are typical of such systems.

## **SMOKE FORMATION**

Smoke is generated in oilheating appliances for a number of reasons. In general, particulate matter may contain three groups of products: 1. Soot, which is formed via the fuel vapor reacting with the oxygen in a combustion/pyrolysis process. This mechanism is favored under fuel-rich conditions and is referred to as gas phase soot. It may also contain cenospheres (or oil coke) which are produced from cracked fuel or carbon. Oil coke and gas phase soot differ significantly in their structure. Oil coke mostly consists of a small number of large particles. Gas phase soot, on the other hand, is an agglomeration of small particles, typically 50nm in size, formed into chains. 2. There is also the possibility of any inorganic components of the fuel burning to form ash. The above two forms of particulate matter are together termed "black smoke." 3. Finally it may contain any unburned or partially burned droplets. This is termed "white smoke." However, this is only rarely a problem with oilburner applications, as they almost always operate under excess combustion air conditions.

Some fuels have a greater tendency to form smoke than others do. The molecular structure of the hydrocarbon is one of the major parameters determining the amount and rate of soot formation (the other parameters being the fuel/oxidant ratio, the gas temperature and the pressure). Heavier molecules tend to form soot more easily. Therefore, the maximum aromatic content in fuels is specified so as to limit smoke formation in critical applications.

In spray combustion, soot forming conditions are always achieved (at least in part) since the region between the droplet surface (or evaporated droplets) and the surrounding flames is always fuel-rich. Inevitably soot is always

produced in this region during the combustion of hydrocarbons. This is the reason the flame zone exhibits a yellow luminosity. The only exception to this occurrence would be in the case of pre-vaporized spray combustion where the flame zone appears blue.

The amount of soot produced in this way may be greatly reduced if the droplet is partially vaporized prior to burning. The soot yields obtained thus are primarily influenced by the injection velocity and the droplet size. Small droplets are less prone to smoke formation. Also, high injection velocities, whether actual or relative to the incoming air, should also be realized to minimize smoke formation. Therefore, higher pump pressures can be expected to yield lower smoke levels both due to a reduction in drop size and an increase in droplet injection velocity or a reduction in the air velocity.

Solid residues are also formed from cracking of the heavier components of the fueloil. During the ignition delay period, the liquid droplet loses the lighter components by fractional distillation. Once ignition occurs, the temperature in the central region of the droplet increases resulting in the thermal decomposition of the liquid hydrocarbon. The formation of carbonaceous products from the combustion of such oil has been found to be markedly controlled by the rate at which the center of the droplet attains a temperature high enough for cracking to occur and the length of time it remains at this temperature.

## **CONTROLLING PARTICULATE EMISSIONS**

Generally, the formation of soot or carbon can be minimized by means of the provision of good mixing resulting from turbulence, the maintenance of a high temperature and a sufficient residence time. These three requirements turbulence, temperature and time-are often called 3-T rule. However, the scale of turbulence is also important since smoke and unburned hydrocarbons can originate from turbulent eddies which are fuel rich.

The combustion conditions that can be varied are: (a) the degree of swirl; (b) the extent of recirculation; (c) the combustion intensity; (d) the quality of atomization, which is dependent on the type of atomizer. (e) the spatial distribution of the spray in so much as it determines the local fuel-air ratio.

The adjustment of any of these parameters that will make the spray behave as a premixed gaseous flame will result in the reduction of smoke. In this respect, the key factors are the droplet size, the degree of mixing, relative droplet to gas velocities and the gas composition.

The degree of swirl imparted to the combustion air has a considerable influence. Low levels of swirl produce considerable amounts of smoke because of poor mixing while increasing swirl decreases soot formation. Overswirling, however, results in the increased formation of gas phase soot due to decreased relative velocity between the droplet and the air.

Recirculation of combustion gases will, to a certain degree, reduce soot. This can be achieved either by swirl (internal recirculation) or by actually directing the gases from the flue to the air intake side of the burner (external recirculation). In both cases, the net result is that hot vitiated gases are mixed with the incoming air, increasing its temperature but slightly reducing the oxygen content. The effect of this is to promote droplet vaporization and to prevent diffusion-controlled droplet burning.

## **CONCLUSION**

Burner manufacturers have made great strides in oilburner design since its inception in the early part of this century. The total particulate emissions from oilheating appliances have come down 10 to 15 times since the 1960s to reach levels comparable to natural gas fired equipment (courtesy information published by Brookhaven National Laboratory and U.S. EPA).

In general, the smoke in an oilfired appliance can be controlled by any of the following techniques: 1. Enhance mixing. 2. Decreased droplet size. 3. Increased droplet relative velocity. 4. Cleaner fuels. 5. Higher pump pressures.

Such measures will further make oilheat a cleaner and more reliable source of heat.

## **References**

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