Droplet Size Distributions of Heat Transfer Fluid Aerosols in Air

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ABSTRACT

Heat transfer fluids are widely used in the chemical process industry and are available in a wide range of properties. These fluids are flammable above their flash points and can cause explosions. Though the possibility of aerosol explosions has been widely documented, knowledge about the explosive potential of such aerosols is limited. The aerosol droplet size distributions of heat transfer fluids must be studied to characterize their explosion hazards.

Current research by the Mary Kay O'Connor Process Safety Center involves non-intrusive measurement of such aerosol sprays using a Malvern Instrument Diffraction Particle Analyzer. The aerosol is generated by plain orifice atomization to simulate the formation and dispersion of heat transfer fluid aerosols through leaks in process equipment. A predictive model to relate the characteristic aerosol droplet size to bulk liquid pressure, temperature, fluid properties, orifice size and ambient conditions will be developed. This model will be used to estimate the explosion hazard of heat transfer fluid aerosols.

Introduction

An aerosol is a suspension of solid or liquid particles in a gas. Aerosols of heat transfer fluids (HTFs) consist of liquid droplets suspended in air. HTFs are widely used in the process industry as in heat exchangers. Process equipment inevitably fails sometime during its lifetime, and leaks are one such mode of failure in process equipment. Depending on the conditions, the bulk HTF may be emitted from the leak in the form of a stream, aerosol or vapor or any combination of these.

Vapors of HTFs are flammable above their flash points and have well defined flammability limits. Eichhorn[1] recognized, as early as 1955 that aerosols can explode. Febo and Valiulis[2] have documented the loss history with heat transfer fluids and have pointed out possible causes. In line with their thoughts, more research is needed to quantify the aerosol explosion potential of heat transfer fluids. The hazardous nature of aerosols or mists has also been discussed by other researchers[1,2,3,4].

The process by which aerosol is created from bulk fluid is called atomization. There are two methods by which an aerosol can be generated from a leak. The first method involves the mechanical break up of a leaking stream of the HTF, and the second involves the re-condensation of the leaking vapor into aerosol.

The HTF aerosol droplet sizes that can be generated by the above two methods are very different. While re-condensation produces aerosol droplets of sizes around 10 microns[1], mechanical break-up yields droplet sizes in the 30 to 60 microns range[5]. The smaller droplets produced by the re-condensation process will produce a more dense aerosol, which can disperse to a greater distance. In the case of mechanical breakup, the larger droplets will burn at a faster rate[1]. Therefore, aerosols can be a hazard even below their flash point. The larger enthalpy per unit volume of aerosols when compared to vapors results in explosions that are far more devastating.

Most consequence analysis studies of aerosol dispersions use computational fluid dynamics software packages such as FLUENT, which can provide temporal distributions of aerosols of an assumed droplet size distribution. It is not documented how well these distributions are related to the fluid properties and the operating conditions. Knowledge of the atomization process will help guide further studies on the explosive nature of aerosols.

Research by the Mary Kay O'Connor Process Safety Center has established functional relations between the operating conditions and the drop-size distributions of the resulting aerosols. The main aim of this research is to study the effect of operating conditions on the drop-size distributions of HTF fluid aerosol in air and to develop models to relate them to fluid properties.

Experimental Details

Samples

Continuing with previous research by the Center, a larger number of HTFs is to be studied. A summary of some fluids to be studied is provided in Table 1.

Apparatus

The apparatus developed for the aerosol studies is shown in Figure 1. It consists of a fluid cell, a positioning system, exhaust system, and the Malvern Laser Diffraction Particle Analyzer (Malvern Laser). The fluid cell is a 4.9 liter aluminum cylinder with an internal diameter of 14 cm and a height of 26 cm. To simulate leaks, orifices are drilled into brass plugs. The positioning system comprises of two precision rails for the X and Y directions. The X direction represents the direction along the centerline of the spray from the orifice, and the Y direction represents the radial direction perpendicular to the X direction. The exhaust system consists of a collection chamber for the spray and a mist separator that removes all aerosol above the 5 micron size. The exhaust system also includes an explosion proof blower to remove the vapor and aerosol phases.

The Malvern Laser consists of a 2mW Helium-Neon laser tube and a ring diode detector. The laser beam is a collimated monochromatic beam of wavelength 780-662 nm and 1.8 mm in diameter. When the aerosol droplets pass through this beam, they diffract the light by amounts inversely proportional to the droplet size[6]. This diffracted light falls on 31 concentric ring diodes in the detector with each ring detecting a certain size range of droplets. The light intensities on each of these diodes are converted into drop-size data by a computer. A schematic of the diffracted light is shown in Figure 2. The Malvern

Laser measurement technique for aerosols has been widely studied in the area of automotive fuel spray combustion[7].

Experimental Procedure

The HTF in the fluid cell is heated to the required temperature using heating tape and is pressurized with nitrogen gas to propel it through the orifice. Measurement of the HTF temperature and pressure are made as close to the orifice as possible. Upon pressurization the heated HTF is sprayed through the laser beam and into the collection chamber. Each measurement of the drop size distribution is an averaged value of 500 diode sweeps.

The Malvern software estimates the Sauter Mean Diameter (SMD) of the aerosol spray using the Rosen-Rammler model. The Sauter Mean Diameter is defined as the diameter of a uniform equivalent drop set with the same total volume and the same surface of all drops as in the real set.

$$D_{32} = SMD = \frac{\sum D^3 \Delta n}{\sum D^2 \Delta n} \tag{1}$$

The advantage in using the SMD to characterize the mean drop diameter is that it yields important information for droplet transport phenomena. For example[8], the heat exchange between an aerosol drop and the surrounding air is a ratio of the heat required to increase the drop temperature by ΔT to the heat consumed from the air at a temperature difference of ΔT .

$$D_{32} \approx \frac{\sum \rho_L \left(\pi D^3 / 6\right) \Delta T \Delta n}{\sum \alpha \pi D^2 \Delta T \Delta n} \tag{2}$$

The uncertainty in the measurement of SMDs by the Malvern is estimated to be ± 5 micron. Photographs of the sprays at various conditions help to interpret the drop size data in the transition regions. Non-spherical drops characterize these regions, where the stream breaks up into aerosol. In these regions the Malvern Laser reports drop sizes that are inconsistent with reality because the Malvern assumes the drops are spherical.

Experimental Results

Prior to using a system in which the aerosol is released vertically downwards, a system was used in which the aerosol was sprayed horizontally. But this alteration improves the spray symmetry and allows more accurate tracking of the spray centerline. The horizontal spray system was used to study an alkylated aromatic HTF.

Atomization

Atomization is the process by which aerosol is produced. Here, atomization is induced by forcing the liquid out through a small orifice to emulate a leak in a process system. The liquid stream upon leaving the orifice is destabilized by the friction forces between the air and the liquid surface. These aerodynamic forces cause disturbances in the surface of the stream. If these disturbances are large enough to overcome the surface energy of the stream, the stream breaks up. This break-up results in the formation of non-spherical segments known as ligaments, which break-up further until they are small enough to form stable spherical drops[8,9].

The atomization process is easily distinguishable into three zones as indicated in Figure 3: AB represents the compact stream, BC the disintegration zone, and CD the fully atomized zone. These zones are confirmed by photography at different spray conditions, as indicated in Figures 4- 6.

The operating conditions such as temperature, pressure, and orifice size are varied and their effects on the drop size distributions are studied. Ohnesorge has showed that as the pressure increases, the stream break-up is much more effective because the friction between the stream and the air is greatly increased[10]. The data and the photographs of the sprays confirm this behavior. Table 2 provides a summary of the spray break-up characteristics under the various studied conditions.

Summary of the drop size distribution data

The atomization of the alkylated aromatic was studied at three pressures (1135, 2170, and 3549 kPa), five temperatures (80, 100, 120, 150, and 190 °C) and two orifice sizes (0.20 and 0.36 mm). Measurements were taken along the centerline from near the nozzle to approximately 450 mm away from it in a horizontal direction. At distances very far away from the nozzle, the ambient conditions have a far greater effect on the atomization characteristics of the spray. The primary aim of this research is to study the effect of operating conditions on the atomization process. Hence, the range of measurements was limited to 450 mm.

Figure 7 is an example of the effect of pressure on the drop size distributions of the aerosol. An increase in the injection pressure results in a decrease in the SMD of the aerosol. Higher pressure causes the fluid to be ejected at a higher velocity, which results in a greater friction between the liquid stream and the surrounding air. This results in larger disturbances on the surface of the stream, which break-up the stream into smaller drops. It is also seen that a pressure increase causes the liquid stream to break up closer to the nozzle, as shown in Table 2.

The effect of temperature on the drop size distribution is more indirect. Temperature alters the physical nature of the fluid by lowering its surface tension, viscosity, and density and this makes the fluid stream more susceptible to disintegration. Similar to the effect of pressure, but to a lesser extent, an increase in the temperature causes the stream to break up closer to the orifice. An increase in temperature of the HTF decreases the SMD of the aerosol. The effect of temperature on atomization is more pronounced at the lower pressure of 1135 kPa. At higher pressures (2170 and 3549 kPa) the effect of pressure is more dominant. The effect of temperature on atomization is shown in Figure 8.

A change in the orifice size exhibited similar trends with respect to temperature and pressure. However, the measured SMDs were higher than those from the smaller orifice size.

Conclusions

This research has demonstrated that there is a dependence of drop size distributions on the operating conditions. The most important conclusion is that significant quantities of aerosol are formed from HTFs at conditions well below their flash points. However, there are threshold conditions below which significant amounts of aerosols were not formed in the tested ranges.

Operating conditions had a significant effect on the drop size, atomization distance, and the amount of aerosol generated. These effects can be used in a number of ways to prevent the formation of aerosols. Design criteria for heat transfer equipment can incorporate these results to operate under conditions which will not be conducive to stream break-up. The leaking stream would then collect into less hazardous pools instead of dispersing into the surrounding air.

Placing obstacles in the path of leaking streams, before they break-up into aerosols, and guard surfaces around potential leak zones can be used in this regard. The use of additives to alter the physical properties of the HTFs may also abate the formation of aerosols.

Future Research

The aim of this ongoing research at the Mary Kay O'Connor Process Safety Center is to understand the mechanisms of HTF aerosol formation through leaks in process equipment. This research includes studying a range of industrial fluids and developing models that can predict aerosol drop sizes, formation distances and dispersion concentrations. These models will help to relate aerosol dispersions to the leak conditions and the bulk fluid properties. Using computational fluid dynamics packages, such as FLUENT, we can then simulate the temporal and spatial concentrations of aerosols in air. The research will be extended to study the effect of additives on the atomization characteristics of the HTFs. Finally, the study of aerosol combustion as a function of drop-size distributions, concentrations, and fluid properties will be used to estimate the upper and lower explosive limits of HTF aerosol/air mixtures.

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Symbols

D_{32} = Sauter Mean Diameter, SMD, micron

D = Mean droplet diameter corresponding to each ring diode

Δn = Number of drops measured by each ring diode

ρ_L = Density of the liquid

c_L = Specific heat capacity of the liquid

α = Thermal conductivity

ΔT = Heat transfer temperature gradient between the drop and the air

L_C = Length of the compact liquid stream

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