A FULL-SCALE CUP BURNER FOR THE TESTING OF GASEOUS AND LOW VOLATILITY AGENTS

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INTRODUCTION

The internationally approved method for measuring the fire suppression efficiency of gaseous fire suppressants uses apparatus and procedure called the cup-burner method. It was originally developed by ICI in I970 and refined in 1973 [1]. Since then many papers have been published about the design and measurements of extinguishing concentrations using cup burners [2-7]. The apparatus consists of a glass chimney containing a small flame cup filled with a liquid fuel. Air and ageni are supplied to the bottom of the chimney. mixed, and then allowed to pass by the ignited fuel. The amount of agent is then increased until the flame is extinguished and the concentration of agent calculated. A full-scale cup burner has now been designed and built at Kidde International Research. It conforms to the draft ISO standard 14520 [8] and the British standard 233: 1996 [9]. It has several novel features that make it a versatile research tool. The design of the KI Research cup burner is explained in this paper. In addition, results of the testing of HFC-227ea, nitrogen and Halon 1011 are given.

OVERALL CUP-BURNER DESIGN

The novel features of the KI Research cup burner are as follows:

- A stainless steel cup with regulated fuel heating and cooling. Cups are usually made of glass. Stainless steel is easier to machine consistently and is not affected by hydrogen fluoride.
- A recirculating fuel supply with a double weir device for the control of the cup fuel level.
- A heated aluminium base. Heating of the agent and the air/agent mixture allows the examination of relatively low volatility agents.
- An electronic control system, which regulates the temperature of the base. fuel, agent metering valve and agent input pipe and displays the temperatures of the base, fuel, agent input pipe and air/agent mixture.
- An electronically-controlled metering valve for precise agent delivery.
- An electronic balance with PC data logging for measuring the rate of agent input. The extinguishing concentration of an agent may be calculated from this data.
- A diaphragm pump for the collection of grab samples for concentration measurements by Fourier Transform Infrared (FTIR) Spectroscopy.
- A real-time oxygen meter, intended to be used for non-infrared absorbing agents such as nitrogen.

The cup burner seen in Figure 1 and Figure 2 (technical drawing). The positions of thermo-couples (denoted as T/C) and of gas sampling for FTIR analysis or oxygen concentration ineasuremeni are also shown in Figure *2*. All aluminium parts were anodised.

To ensure efficient mixing, the agent was introduced into the air stream before it passed into the cup burner. Further mixing inside the cup burner was ensured using glass beads in the base (location [Figure 2]). For relatively low volatility agents (boiling point >20 ºC, e.g., Halon 1011), it was necessary to heat the agent metering valve (the point where the adiabatic expansion of the agent took place), air/agent input pipes, and base of the cup burner. Heating was not required for relatively high volatility agents (boiling point <20º C, e.g., HFC-227ea and nitrogen). **A** laminar flow of the air/agent mixture was created using a hexagonal aluminium flow straightener (dimensions: side of hexagon = 4 mm, length of hexagonal tubes = 75 mm; location [Figure 2]).

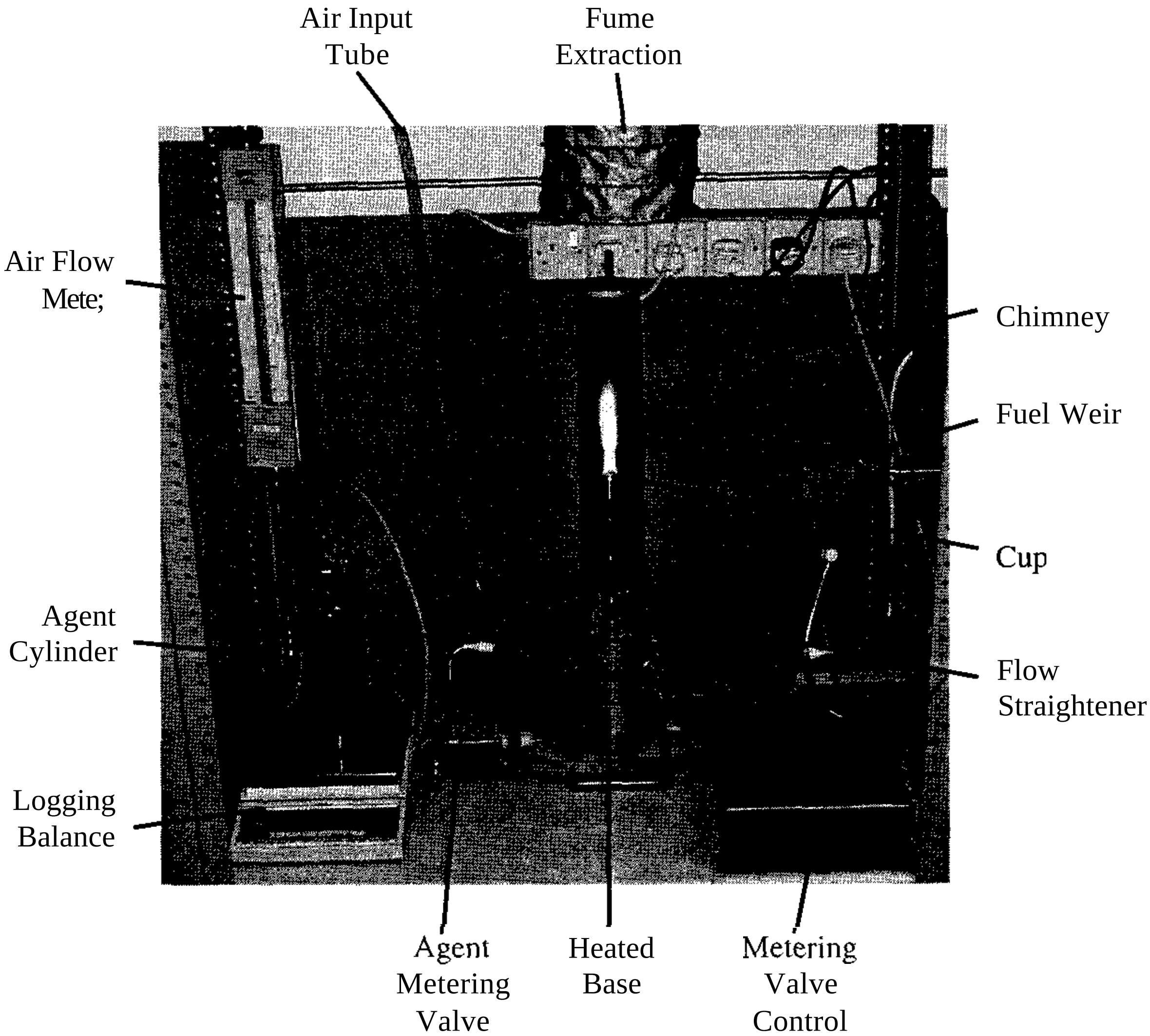

Figure 1. Cup burner.

CUP-BURNER DESIGN

As mentioned previously, for ease of manufacture, the cup (Figure **3)** was made of stainless steel in two parts that were brazed together. **It** had an internal diameter of ***26*** mm and a wall thickness of 1 mm. The lip had a 45-deg chamfer. The cup was mounted in copper pipe through which the fuel, liquid-cooling, and heater connections were passed. **The** temperature of the fuel in the cup was controlled with a Nichrome wire heater and a thermocouple situated 5 mm below the surface

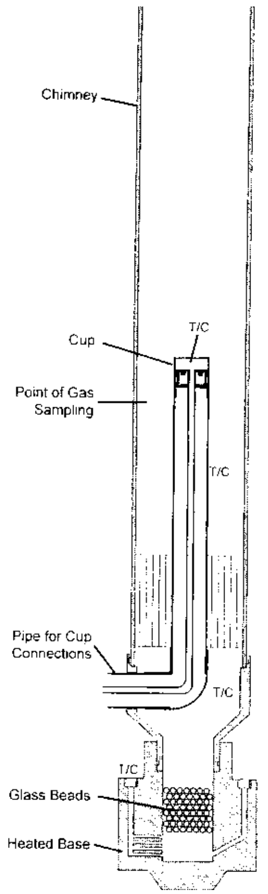

Figure 2. Technical drawing of the cup burner

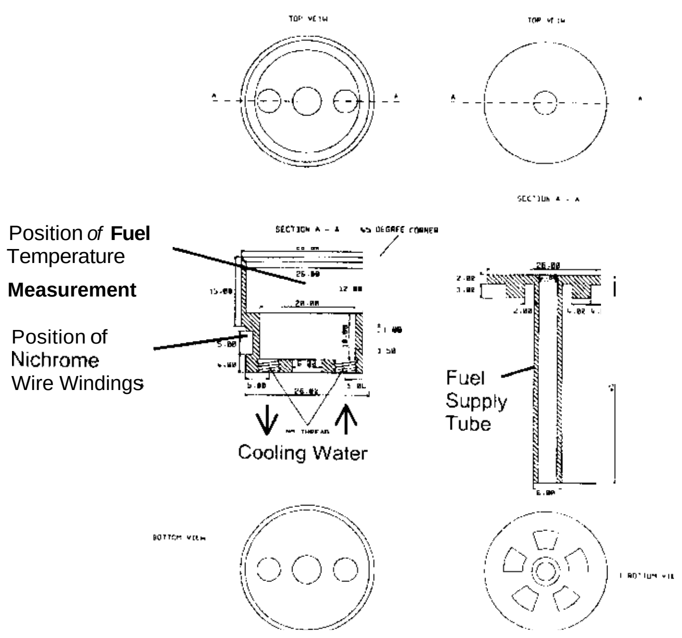

Figure 3. Cup-burner details.

of the fuel (Figure 2). In addition, the temperature of the 1:1 water:ethylene glycol coolant was also controlled. This gave temperature control of the lighted fuel from about 25 to 95 °C.

EXPERIMENTAL

Initial testing followed the ISO procedure [8]. The base of the cup burner was maintained at 40 °C, which regulated the air/agent mixture at about this temperature. Data recorded for each test included the atmospheric pressure, the temperature of the air/agent mixture at extinguishment, the initial fuel temperature, the fuel temperature at extinguishment, the air flow at extinguishment, the oxygen concentration at extinguishment, and, where FTIR analysis was required, the relevant quantitative infrared absorption spectrum.

The oxygen concentration was measured in real time during all tests. The oxygen analyser was normalised to an ambient oxygen concentration of 20.95 vol% before each test. It also had an internal correction for temperature and atmospheric pressure variations. Nitrogen extinguishing concentrations were calculated from these measurements. HFC-227ea and Halon 1011 extinguishing concentrations were measured by FTIR spectroscopy of grab samples that were collected in Tedlar hags immediately after extinguishment of the flame. The FTIR spectrometer was calibrated prior to the tests and involved the injection of syringe samples of the agents. Syringes were used to inject the test sample into the FTIR spectrometer. The measurements were corrected for atmospheric pressure variations.

RESULTS

When initial measurements with this cup burner were compared with those from a standard ICI-style cup burner, it was found that less agent was required for extinguishment. A thorough study was undertaken to identify why.

EFFECT OF FUEL TEMPERATURE

The ISO procedure for cup-burner measurements stipulates that an initial n-heptane temperature of 25±1 °C is used. However, the fuel temperature cannot he regulated in an ICI-style cup burner and the fuel temperature increases while the flame is alight. Thus, at extinguishment the fuel temperature is much higher than 25 °C, but this is not measured. As a result, the fuel temperature may vary significantly between different tests and equipment. In the KI Research cup burner there is cooling and heating of the cup. Therefore, it was possible to heat and regulate the fuel to a set temperature. During the preburn the n-heptane was heated by the flame, which raised the fuel temperature above the control temperature. However, as the point of extinguishment was approached, the flame size reduced allowing the desired temperature to be achieved again. The actual n-heptane temperature was recorded along with other parameters at the point of extinguishment. Tests were carried out with n-heptane temperatures from 25 to 97 °C (bp of *n*-heptane) at air flows of 10 to 50 L/min.

For reasons given above, it was presumed that when tests were carried out with low initial fuel temperatures in the KI Research cup burner, the fuel temperature at the point of extinguishment would be lower than in a typical ICI-style cup burner. The effect of the n-heptane temperature on the required extinguishing concentration of HFC-227ea and nitrogen was investigated. The results of tests at different fuel temperatures at the point of extinguishment and at different air flows are given in Figures 4 and 5. On each graph, 3rd order polynomial lines of best fit through the 20, 30, and 40 L/min air flow data are shown.

In the graph for HFC-227ea (Figure 4), the extinguishing concentration increases sharply with fuel temperature over the range 25 to 45 °C to a shallow peak in the range 45 to 60 °C. At **a** fuel temperature of SO °C and an air flow of 30 L/min the extinguishing concentration is 6.8 $\pm$ **0.1** vol%. The error limits quoted are the 95% confidence limits. **At** higher temperatures. there is then a steady decrease in the extinguishing concenlration until the fuel boiling point is reached.

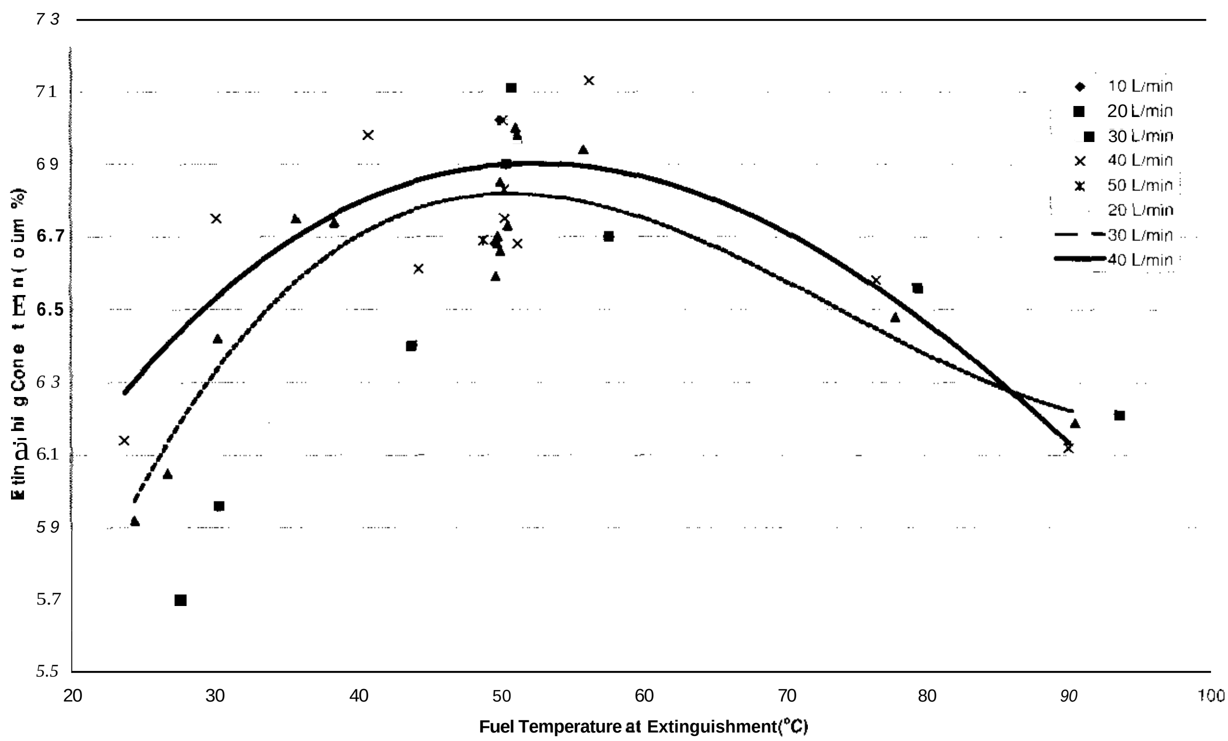

Figure 4. Variation of HFC-227ea extinguishing concentration with fuel temperature.

In addition, for fuel temperatures over the range 25-50 °C, the measured extinguishing concentration shows a dependence on air flow. At a fixed fuel temperature, the lower the air tlow the lower the extinguishing concentration. At the peaks and at higher temperatures, the extinguishing concentration becomes independent of air flow (see below) in the range of 20 to 40 L/min.

The graph for nitrogen (Figure 5) shows **a** similar increase in the extinguishing concentration as the fuel temperature is increased up to 50 °C where the peak extinguishing concentration varies between 31 and 33 vol% in the range of air flows studied. Above 50 °C, the extinguishing concentration slowly decreases with the fuel temperature. As with HFC-227ea, a lower air flow causes a lower extinguishing concentration for fuel temperatures below about 60 "C. Above this, the extinguishing concentration becomes less dependent (within experimental error) on the air flow lor flows in the range of 20 to 40 L/min.

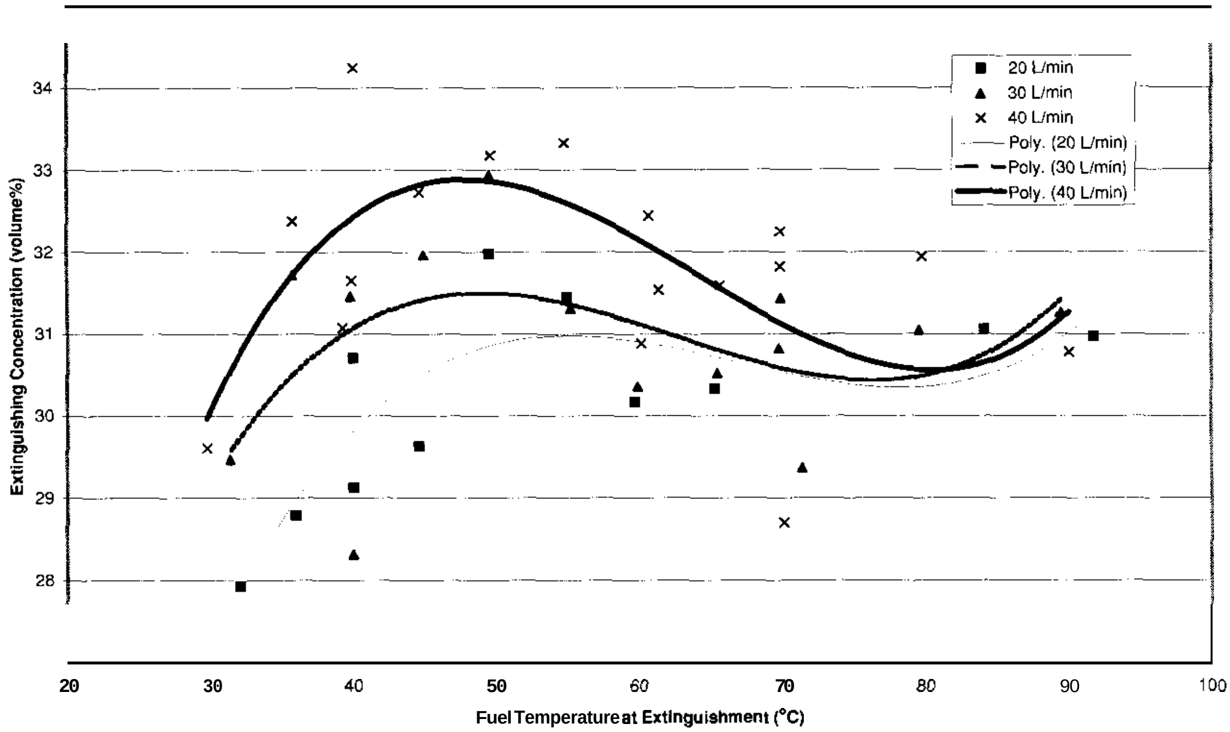

Figure 5. Variation of nitrogen extinguishing concentration with fuel temperature.

There is greater scatter in the nitrogen extinguishing concentration data. This is probably because concentration measurements based on the oxygen meter are **less** precise than those based on FTIR measurements.

DEPENDENCE OF EXTINGUISHING CONCENTRATION ON AIR FLOW

Previous measurements using this cup burner have indicated that there is not a marked dependence of the extinguishing concentration on air flow. The ISO procedure for cup-burner measurements requires that the range of air flows is found over, which the extinguishing concentration is at a maximum and independent of the air flow [8]. Results obtained for HFC-227ea with a *n*-heptane temperature of 50 °C are given in Figure ***6***. It appears that within experimental error, the extinguishing concentration is independent of the air flow between 10 to *50* L/min.

RATIONALE

As the fuel temperature increases, the flame in the cup burner becomes taller, and there is a greater rate of fuel vaporisation. **A** graph of the rate of free burning (without extinguishing agent present) against temperature for n-heptane is given in Figure 7. The rate increases from ***5*** to 20 mg/s when the temperature is raised from 20 to ***60*** °C. In addition, the flame exhibits greater lift off at extinction (as high as 40 mm) as the fuel temperature is raised. Furthermore, the lifted flame becomes more and more blue in colour due to entrainment of air at the rim of the cup, which indicates some premixed character. This phenomenon has been previously observed for

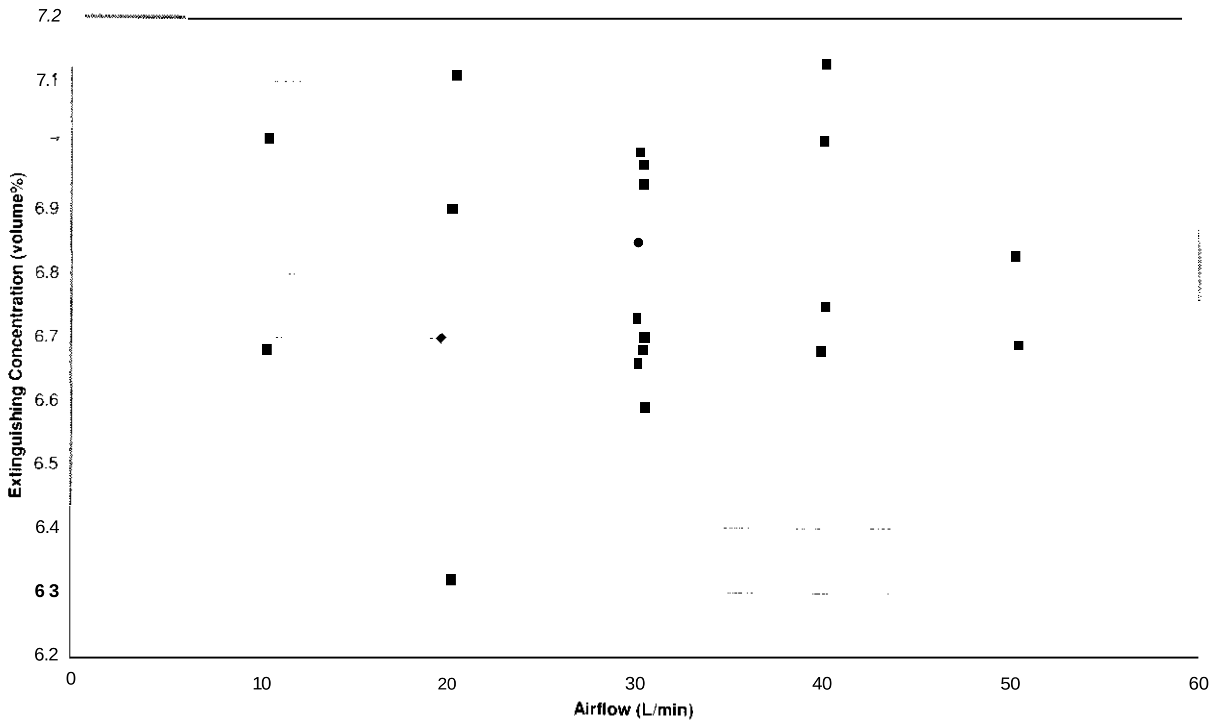

Figure 6. Dependence of the HFC-227ea extinguishing concentration on air flow.

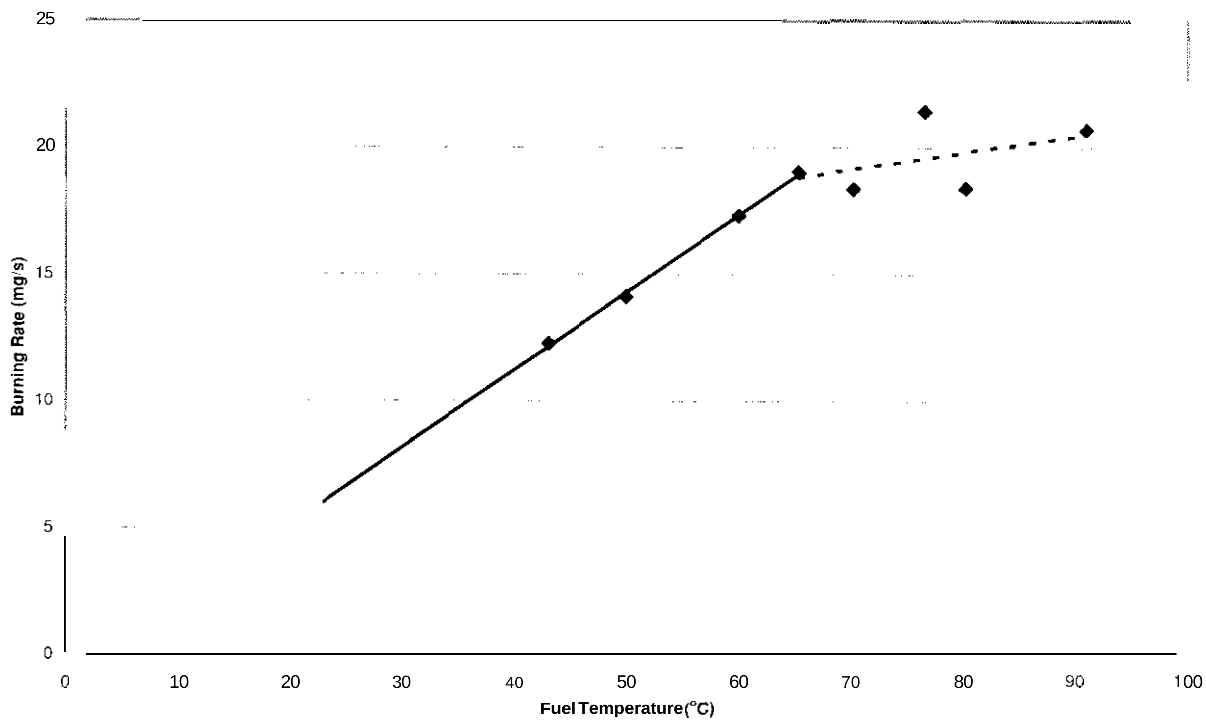

Figure 7. Dependence of the n-heptane free burning rate on temperature.

diffusion flames [10]. The result of this premixed character is that the flame is harder to extinguish because premixed flames require higher extinguishing concentrations than diffusion flames. For example, HFC-227ea has a propane inerting concentration of 11.5 vol% [11].

The equivalence ratio is not usually considered for, or is relevant to, diffusion flames. However, it has been shown in this study that there is an increased mass flow rate of the heptane fuel into the flame as the fuel temperature increases. Therefore, the results for HFC-227ea and nitrogen have been re-expressed on the basis of the nominal fuel/air equivalence ratio. This parameter was calculated from the rate of free burning of the n-heptane fuel, at the appropriate fuel temperature, before the agent addition was started, assuming that each mole of heptane required 11 moles of oxygen for complete combustion. Note this is not the equivalence ratio at the point of extinguishment, when the flame size and, hence, the rate of consumption of n-heptane would be considerably reduced below the levels given in Figure 7.

By plotting the extinguishing concentration against the nominal equivalence ratio in Figures 8 and 9, the curves for the different air flows are separated along the abscissae. This does not imply that different stoichiometries are occumng, but it is due to the fact that not all the air (i.e., oxygen) supplied to the cup burner can become involved with the flame. Radial diffusion rates of oxygen through the air in the cup burner are very much slower than the axial linear velocity of the air/agent stream upwards through the chimney. The greater the air flow, the greater the excess air and the lower the nominal equivalence ratio. In Figure 8, it is also clear that the peak values of the extinguishing concentration are all in the region of 6.8 vol%, i.e., there is a "plateau" value with respect to the air flow rate. Figure 9, by contrast, indicates that for nitrogen a similar "plateau" of peak values does not occur. This may be due to the greater overall volumetric flow rates (or axial linear velocities) with the less efficient agent.

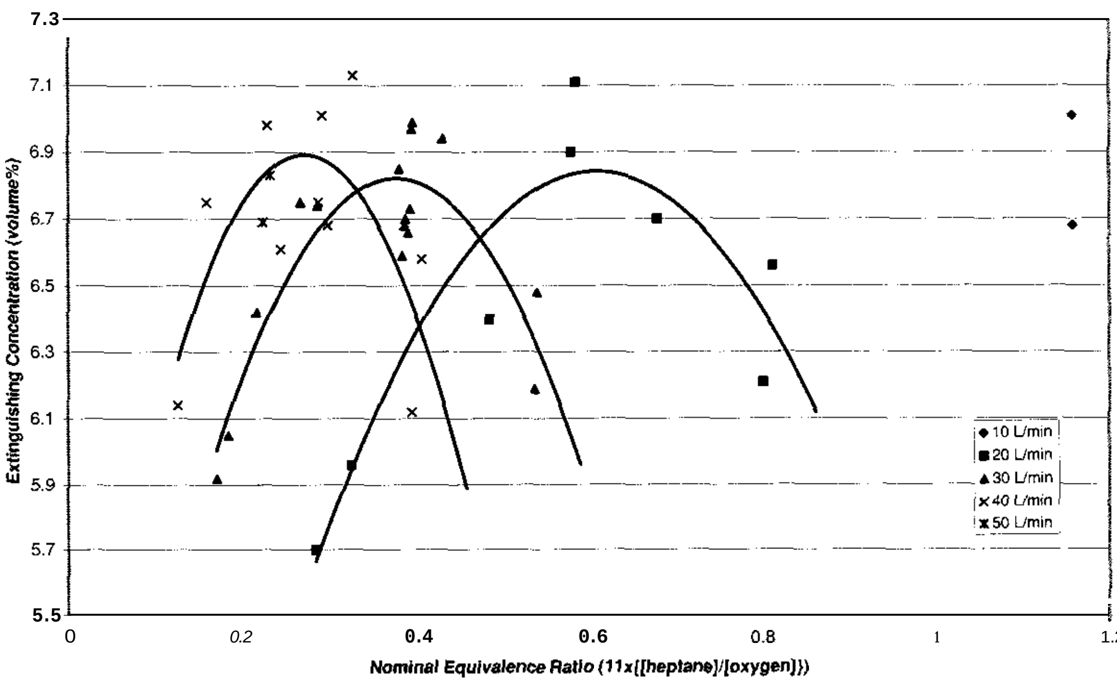

Figure 8. Variation of HFC-227ea extinguishing concentration with nominal equivalence ratio.

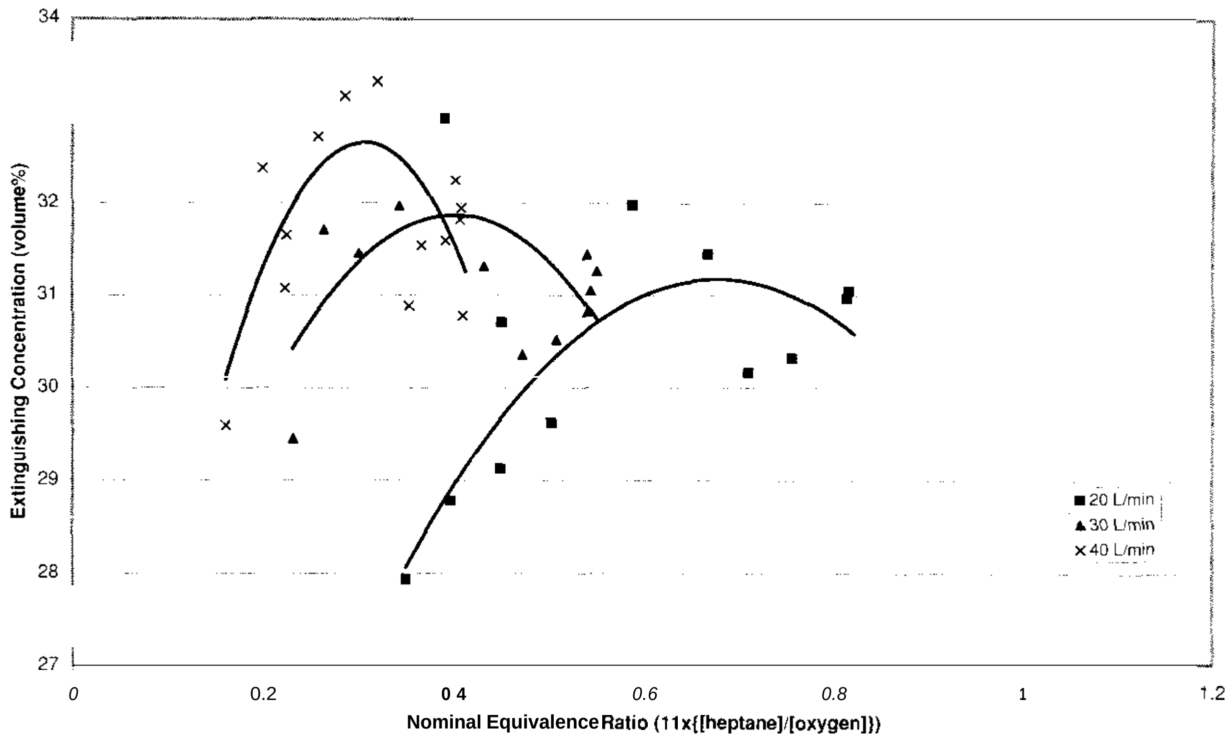

Figure 9. Variation of nitrogen extinguishing concentration with nominal equivalence ratio.

Figure 8 also shows some data for 10 Wmin air flow (and *50* °C fuel temperature). which have nominal equivalence ratios on the air lean side. This suggests that results with such low air flow rates should be treated with caution.

EFFECT OF HUMIDITY

Water vapour, a suppressant in its own right, has a predicted extinguishing concentration for heptane of 25 vol% [12, 13]. Therefore, it is much less efficient than HFC-227ea but somewhat more efficient than nitrogen. Most cup burners use compressed air as the source of air, and this is typically very dry (relative humidity <1%), whereas real fires burn in atmospheres with upwards of 40% relative humidity. Some initial work to study the effect of humidity on extinguishing concentration has been carried out by passing the compressed air supply to the cup burner through heated distilled water. A humidity meter was then used to check the humidity of the air flow in the cup burner. Tests undertaken with HFC-227ea (fuel iemperature of SO °C, air flow of 30 L/min) indicate that the extinguishing concentration was reduced from 6.8 ± 0.1 vol% at a relative humidity of about 0% to about 6.4 vol% at a relative humidity ***of*** about 100%.

LOW VOLATILITY AGENTS

This cup burner was intended to be able to measure the extinguishing concentration of agents that are liquids at room temperature. It has now been used successfully to measure the extinguishing concentration of Halon 1011 (Formula: CH_2BrCl, bp: 67 "C). A value of the extinguishing concentration of 4.1 ± 0.2 vol% was measured at a fuel temperature of 50 °C and an air flow of 30 L/min.

CONCLUSIONS

- The cup burner apparatus described above, with facilities for handling low volatility agents and for controlling the fuel temperature, has provided new understanding of factors affecting performance of gaseous suppressants.
- The ISO standard stipulates an initial fuel temperature of 25 ± 1 °C, but does not say what the fuel temperature has to be at extinction. The results presented above indicate that this can have a significant effect on the measured extinguishing concentration. Furthermore, it is possible that consideration of this parameter can go a long way to explain much of the inter-laboratory variation in measured extinguishing concentrations by the cup-burner method. It may also provide insight into some of the discrepancies that have arisen in the past between large-scale fire suppression tests and laboratory measurements. In general terms, from the results presented above, it seems that the fuel temperature at extinction in the cup burner should be in region 50 ± 5 °C. If the extinguishing concentrations measured in this study are compared with results from other ISO cup burners, it seems likely that the natural fuel temperature achieved by the ISO method is around 50 °C.
- During this study, the agent extinguishing concentration measurements were corrected for variations in ambient atmospheric pressure in agreement with the ISO standard.
- An air flow of 10 L/min does not supply sufficient oxygen for stoichiometric combustion in the cup burner. A minimum concentration of 15 L/min is recommended.
- As the humidity of the air supplied to the cup burner is increased, the agent concentration requirement is reduced.

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