

THE CUP BURNER METHOD – A PARAMETRIC ANALYSIS OF THE FACTORS INFLUENCING THE REPORTED EXTINGUISHING CONCENTRATIONS OF INERT GASES

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INTRODUCTION

The cup burner method has become an internationally accepted standard procedure for establishing the extinguishing concentration of gaseous fire-fighting agents. Specifications for the determination of extinguishing concentration using the cup burner method are set out in ISO 14520, Part 1: Annex B [1] and NFPA 2001 Appendix B [2].

Significant inconsistencies appear to exist in the cup burner extinguishing concentrations submitted to ISO by various laboratories. This observation is particularly pertinent to the case of inert gases. It is thought that variations in measured extinguishing concentrations could be due to different interpretations of the standard operating procedures, which may not be adequately specified in the relevant prescriptive documents.

A previous study has noted the dependence of extinguishing concentration upon various cup burner procedural parameters, but limited quantitative data was given [3]. This paper will describe a systematic parametric investigation into the cup burner method. The fuel used throughout was *n*-heptane and the suppression agents were the inert gases carbon dioxide and nitrogen (referred to in ISO 14520 as IG100). The use of fully instrumented apparatus has allowed the investigation of the effects of changing various parameters. Variables in the method that have been investigated include pre-burn time, the combined air and agent temperature, the rate of agent addition and changes in the combined air and agent flow rate.

EXPERIMENTAL

The ISO 14520 compliant cup burner apparatus extant at Kidde Research has been described previously [4] and additional instrumentation was added as required. Experiments were conducted using the standard conditions specified in Table 1 below, unless otherwise stated:

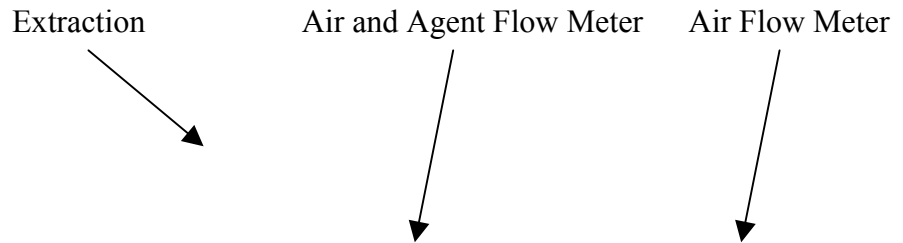
Table 1. Standard Experimental Conditions

Parameter	Kidde Research	ISO 14520	NFPA 2001
Liquid Fuel	n-Heptane	Not Specified	Not Specified
Fuel Temperature / °C	25 ± 0.5	25 ± 3	25 ± 1
Air Flow Rate / L min ⁻¹	40 ± 1	10 - 50	10 - 50
Air / Agent Temperature / °C	25 ± 0.5	25 ± 10	Not Specified
Pre-burn Period / s	90	60 to 120	90 to 120

The experimental strategy was to incorporate specific, controlled changes to the cup burner procedure, in order to observe their effect on inert gas extinguishing concentrations. The investigation of individual parameters was carried out as follows:

COMBINED AIR AND AGENT FLOW RATE

The effect of the combined air and agent flow rate upon the extinguishing concentrations of nitrogen or carbon dioxide was examined in two ways. Tests were conducted either by setting a constant air flow rate of 40 L min⁻¹ and allowing the total flow rate to increase as more agent was added, or by maintaining a constant air and agent flow rate of 40 L min⁻¹. The latter condition was established by using an additional flow meter, inserted in the system downstream from the gas stream mixing point (see Figure 1 below). The air flow rate was then gradually decreased as the agent flow rate increased.



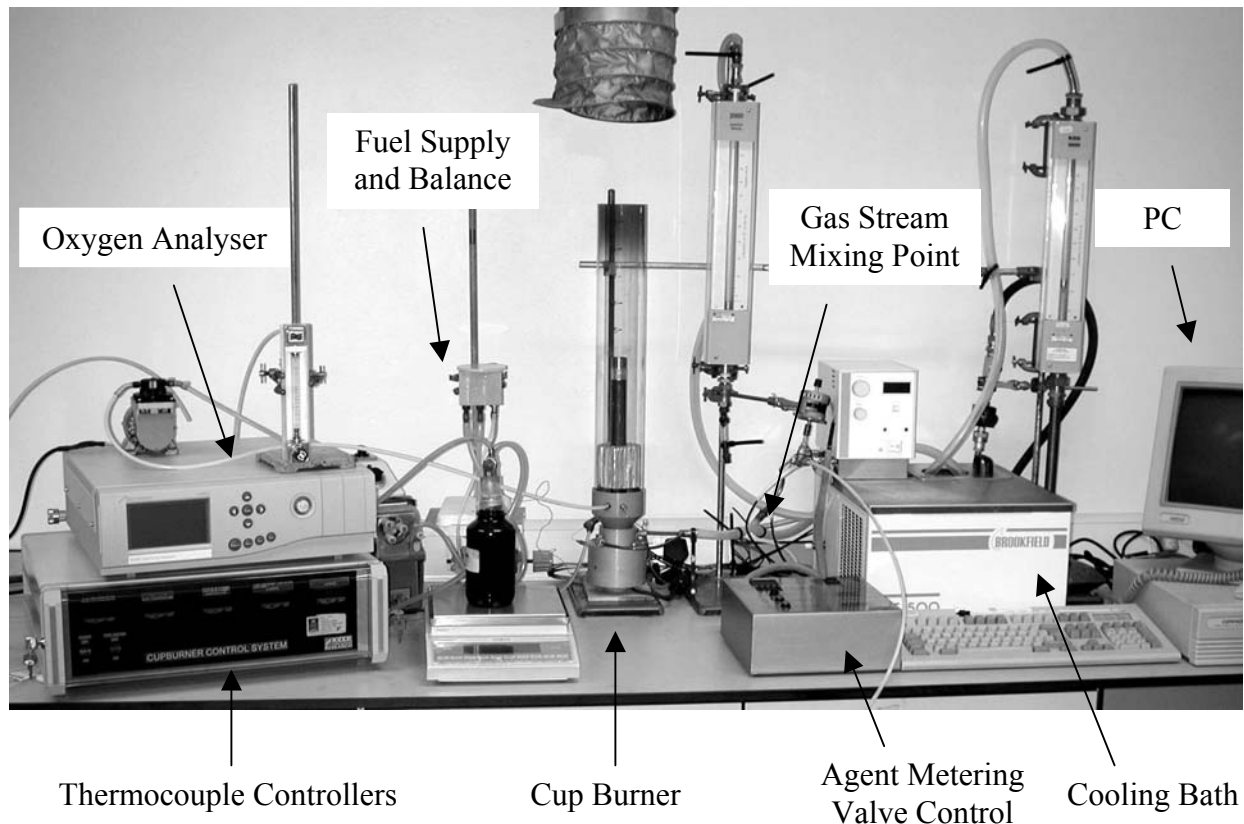


Figure 1. Cup Burner Apparatus

COMBINED AIR AND AGENT TEMPERATURE

The temperature of the combined air and agent gas stream was set at 15, 25 or 35 ± 0.5 °C and cup burner tests were performed for nitrogen and carbon dioxide at each temperature. The temperature was controlled at 15 ± 0.5 °C by means of placing the cup burner base in a cooling bath (ethylene glycol and water mixture). This approach had the benefit of minimising the path length travelled by the gas mixture, which reduced the cup burner response time and any changes in the agent concentration gradient through the piping network. The temperature was maintained at 35 ± 0.5 °C using cartridge heaters located in the cup burner base. Combined air and agent temperatures were monitored using a K-type thermocouple located 125 mm below the top of the cup.

RATE OF AGENT ADDITION

A series of experiments was carried out to evaluate the importance of the rate of agent addition. Extinguishing tests were carried out using a method based on the ISO and NFPA protocols. The standard agent addition rate was defined as when the agent concentration was raised rapidly to

half of the expected extinguishing concentration and then the agent concentration was increased in increments of no more than 1 % of the previous value.

Extinguishing agent addition rates using incremental concentration increases both slower and faster than the standard approach were also investigated. For these tests, the agent concentration was rapidly increased to either one third (slow) or to two thirds (fast) of the expected extinguishing concentration. The agent concentration was then increased in increments of 1% of the previous value until the flame was extinguished.

A “sudden” addition approach was also utilised, where the extinguishing agent was rapidly introduced at a predetermined extinguishing concentration. The sudden addition extinguishing concentration was decreased incrementally and repeated until the flame was not extinguished within 15 seconds. The sudden addition extinguishing concentration was thus defined as the lowest agent concentration that would extinguish the *n*-heptane flame within 15 seconds of agent addition over three consecutive tests.

FUEL LEVEL IN THE CUP

The fuel level was maintained at one of three different positions, either at the lip of the cup, 1 mm below the lip of the cup (at the chamfer), or 1 mm below the chamfer (see Figure 2 below). Cup burner tests were then performed for each fuel level and the fuel temperature at flame extinction was recorded in each case.

INFLUENCE OF THE PRE-BURN PERIOD

In order to evaluate the effects of fuel temperature and flame height on extinguishing concentration, pre-burn times of 60, 90 and 120 seconds were investigated. The fuel temperature was measured using a thermocouple positioned 1 to 2 mm below the fuel surface (see Figure 2 below):

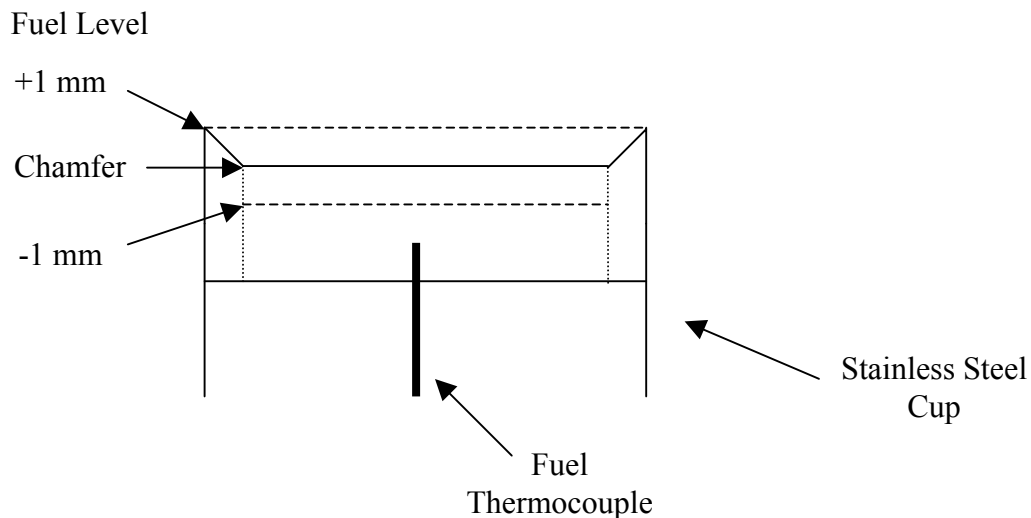


Figure 2. Fuel Levels and Thermocouple Position

GENERAL EXPERIMENTAL INFORMATION

For selected experiments, the flame was recorded on video, in order to allow analysis of changes in the flame geometry in response to alterations in the cup burner procedure. In all cases, the burning rate of the *n*-heptane was determined by placing the fuel reservoir on a logged balance and fuel temperatures were measured as shown in Figure 2. Extinguishing concentrations were established by means of oxygen concentration measurements as described in ISO 14520 and NFPA 2001. A Servomex 4100 gas purity analyser was used for this purpose and was calibrated daily with oxygen at 10.04 and 15.28 % in nitrogen (BOC Alpha volumetric oxygen calibration standards). Oxygen calibration points at 0.00 and 20.95 % were also used. Benchmark extinguishing concentrations of 33.7 and 22.9 volume % were determined for nitrogen and carbon dioxide respectively under standard conditions, and these and all other extinguishing concentrations were measured to ± 0.5 volume %.

RESULTS

COMBINED AIR AND AGENT FLOW RATE

The mean extinguishing concentrations for nitrogen and carbon dioxide obtained at either a combined air and agent flow rate of 40 L min^{-1} or at 40 L min^{-1} of air plus the agent flow rate are summarised in Table 2 below. For experiments using 40 L min^{-1} of air plus the inert gas, the total flow rate for nitrogen at the extinguishing concentration was approximately 53.5 L min^{-1} and for carbon dioxide, 49 L min^{-1} . It can be seen from Table 2 that for carbon dioxide, there was only a slight extinguishing concentration dependence on the total air and agent flow rate outside the range of experimental error. Comparing total flow rates of either 40 L min^{-1} or approximately 49 L min^{-1} revealed extinguishing agent concentration variations of less than 1 volume %.

Table 2. Effect of Air and Agent Flow Rate on Mean Extinguishing Concentration.

Agent	Constant 40 L min^{-1} Air and Agent Extinguishing Conc. / ± 0.5 Vol %	40 L min^{-1} Air Flow Plus Agent Extinguishing Conc. / ± 0.5 Vol %
Nitrogen	31.9	33.7
Carbon Dioxide	22.2	22.9

For nitrogen, there was an increase in extinguishing concentration of 1.8 volume % at the higher total flow rate of approximately 53.5 L min^{-1} . This difference is outside the limits of the experimental error and so appears to represent a genuine, albeit small, effect. The maximum flame height achieved during pre-burn was 210 mm at a constant 40 L min^{-1} air and agent flow compared with 230 mm at the higher combined flow rate. Initial fuel burning rates of about 7 and 10 mg s^{-1} were recorded for the lower and higher combined flow rates respectively.

COMBINED AIR AND AGENT TEMPERATURE

The extinguishing concentrations of nitrogen and carbon dioxide were measured between three and five times at three different combined air and agent temperatures and the resulting data are plotted in Figure 3 below:

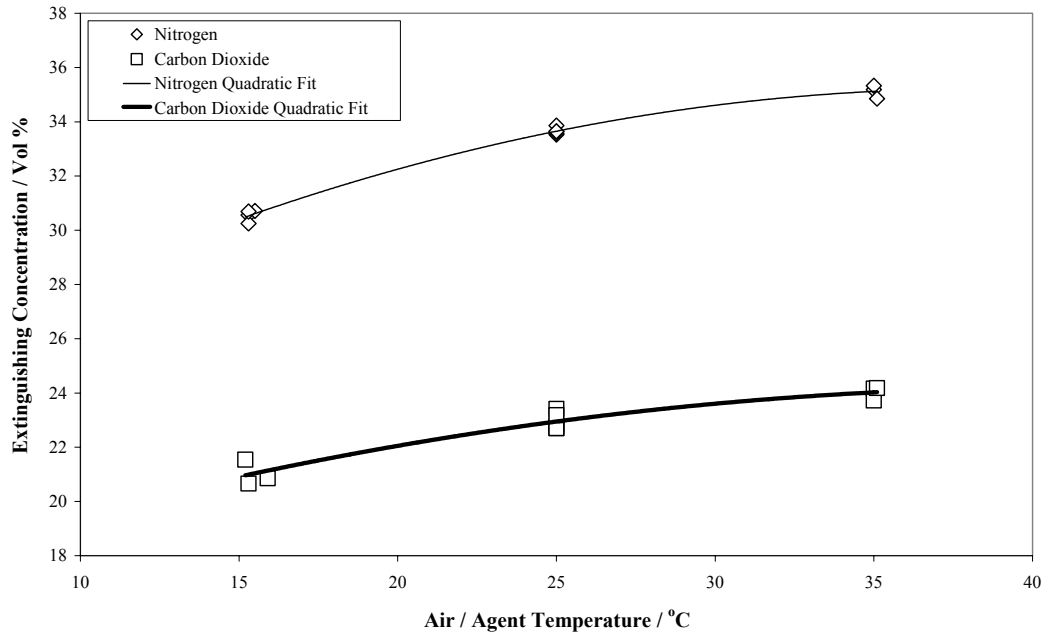


Figure 3. Effect of Combined Air and Agent Temperature on Extinguishing Concentration

The variation of air and agent temperature had a clear effect on the measured extinguishing concentrations of both gases and the data were found to be well represented by simple quadratic functions. The extinguishing concentration data for nitrogen and carbon dioxide at each temperature were closely grouped, with a scatter of around 0.5 volume % about the mean value. It is evident from inspection of Figure 3 that increasing the temperature of the air and agent gas stream led to a consistent increase in the extinguishing concentrations. For nitrogen, the concentration rose from 30.5 ± 0.5 volume % at $15\text{ }^{\circ}\text{C}$ to 35.1 ± 0.5 volume % at $35\text{ }^{\circ}\text{C}$. In the case of carbon dioxide, the concentration increased from 21.0 ± 0.5 volume % at $15\text{ }^{\circ}\text{C}$ to a value of 24.0 ± 0.5 volume % at $35\text{ }^{\circ}\text{C}$. It can be shown that between 15 and $35\text{ }^{\circ}\text{C}$, the additional quantities of nitrogen and carbon dioxide required amounted to some 15 and 14.3 % respectively, i.e. the relative effect was similar for both gases.

It was noted that the maximum fuel burning rate during pre-burn increased from approximately 5.5 mg s^{-1} at $15\text{ }^{\circ}\text{C}$ to 16.2 mg s^{-1} at $35\text{ }^{\circ}\text{C}$. Flame heights at the end of the pre-burn period increased from 210 mm to 240 mm over the same air and agent temperature range.

RATE OF AGENT ADDITION

Extinguishing concentration data for nitrogen and carbon dioxide as a function of increasing addition rate are given in Figure 4 below. Agent addition rate 1 is “slow”, rate 2 corresponds to standard procedure, agent addition rate 3 is “fast” by comparison and addition rate 4 is the “sudden” method as described in the Experimental section.

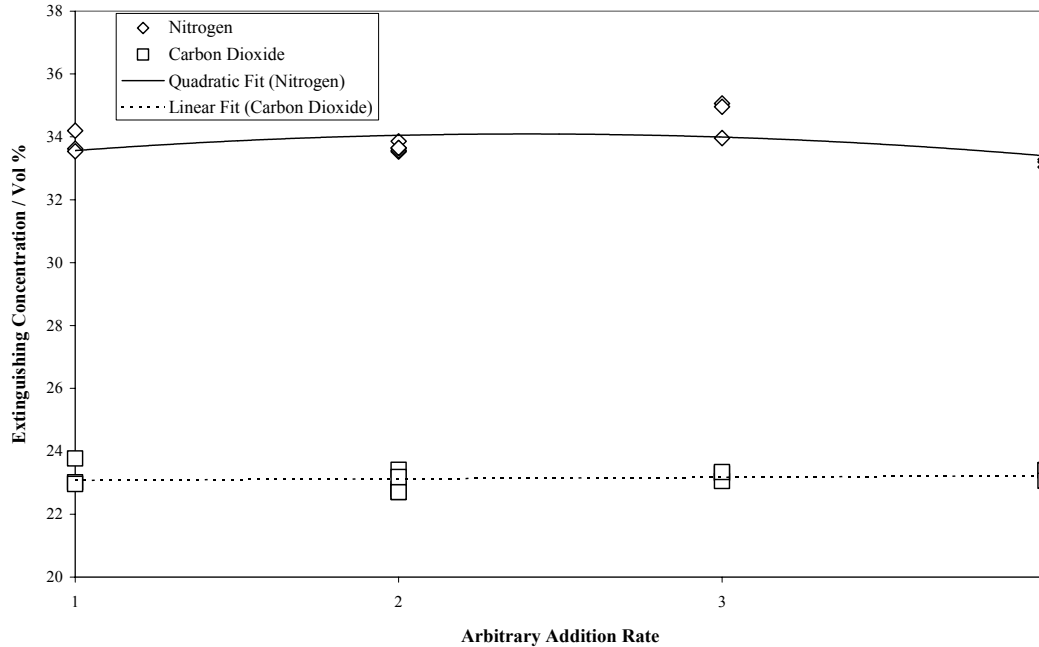


Figure 4. Effect of Agent Addition Rate on Extinguishing Concentration

Nitrogen extinguishing concentrations were shown to have some sensitivity to addition rate, with the highest mean value of 34.7 ± 0.5 volume % recorded at addition rate 3. The lowest mean value of 33.2 ± 0.5 volume % was recorded for the “sudden” addition approach. Carbon dioxide extinguishing concentrations were found to change little according to addition rate, varying from low to high mean values of 23.0 and 23.3 ± 0.5 volume % respectively. Fire out times diminished with increasing agent addition rate and mean values are given in Table 3 below:

Table 3. Mean Fire Out Times.

Agent	Slow Addition Fire Out Time / s	Standard Addition Fire Out Time / s	Fast Addition Fire Out Time / s	Sudden Addition Fire Out Time / s
Nitrogen	268	210	71	14
Carbon Dioxide	125	98	50	8

It was observed that under sudden agent addition conditions, a stable premixed region was formed in the flame and more pronounced lift-off was observed than for incremental agent addition.

FUEL LEVEL IN THE CUP

The extinguishing concentrations of nitrogen and carbon dioxide are plotted versus fuel level in Figure 5 below. Fuel temperatures at flame extinction for each test are also included.

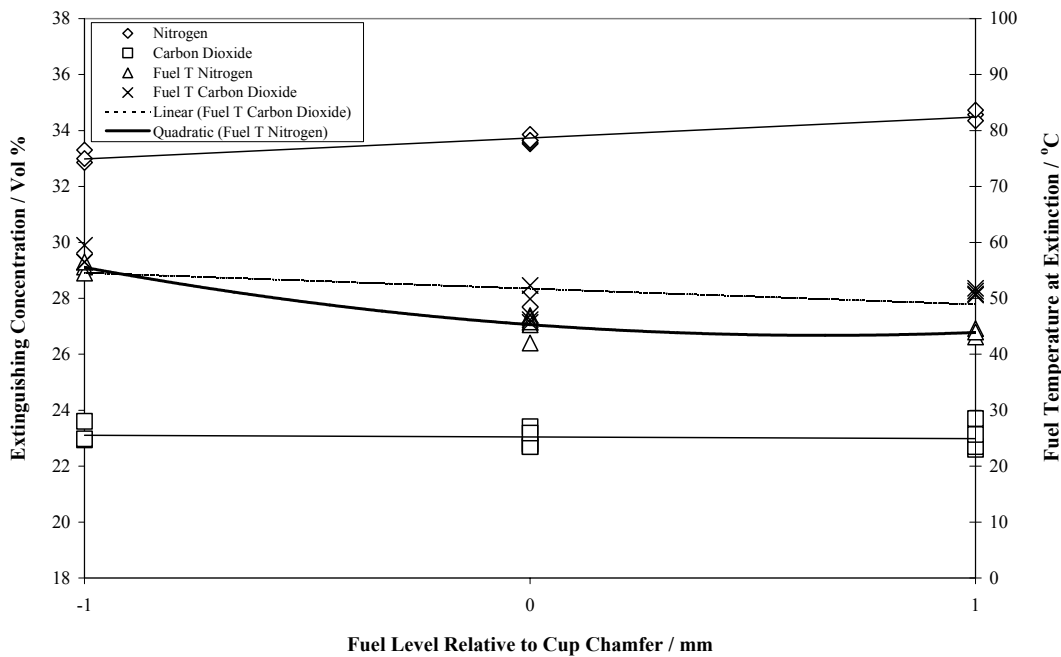


Figure 5. Effect of Fuel Level in the Cup on Extinguishing Concentration

It appeared that for carbon dioxide, there was no significant dependence of extinguishing concentration upon the fuel level. For nitrogen, the extinguishing concentration rose from a value of 33.0 ± 0.5 volume % with the fuel 1 mm below the chamfer to 34.5 ± 0.5 volume % with the fuel level 1 mm above the chamfer, i.e. at the cup lip.

Maximum fuel burning rates during pre-burn were found to increase from 5.2 mg s^{-1} to 15 mg s^{-1} on raising the fuel level from below the chamfer to the cup lip. Maximum flame heights were found to be as low as 190 mm for the lowest fuel level compared with approximately 230 mm with fuel at the cup lip.

Fuel temperatures at flame extinction were found to decrease slightly as the fuel level was increased. The effect was slightly more pronounced for tests involving nitrogen, where the temperature fell from around 56 to 44 ± 0.5 °C when the fuel level was raised from the minimum to the maximum level.

PRE-BURN PERIOD

Mean extinguishing concentrations obtained with three different pre-burn times are summarised in Table 4 below:

Table 4. Effect of Pre-Burn Time on Extinguishing Concentration

Agent	Pre-burn Time / s	Extinguishing Concentration / ± 0.5 Vol %
Nitrogen	60	33.9
	90	33.7
	120	33.9
Carbon Dioxide	60	23.2
	90	22.9
	120	23.3

From Table 4, it can be seen that for carbon dioxide and nitrogen there was very little dependence of extinguishing concentration upon the length of the pre-burn.

Maximum recorded fuel consumption rates varied between 6.0 and 11.0 mg s⁻¹ during pre-burns of 60 to 120 seconds, with the higher rates being recorded for longer pre-burn periods.

It was found that the height of the *n*-heptane flame reached a maximum of approximately 230 mm after 90 seconds and did not increase for 120 second pre-burns. At 60 seconds, the flame had reached a height of only 190 mm.

DISCUSSION

COMBINED AIR AND AGENT FLOW RATE

The data summarised in Table 2 suggest that altering the combined air and agent flow rate has only a minor effect on the extinguishing concentrations of carbon dioxide and nitrogen. One would expect flame stability to be influenced directly by the air flow rate past the cup [5]; a higher total flow rate would carry relatively more air and logically may affect the flame stability to some extent. Increasing the overall flow rate would also lead to a reduced agent residence time in the flame, thereby influencing the likely extinguishing concentration. Another factor that could be of relevance is that fuel burning rates were observed to increase at an elevated air and agent flow rate, together with an increase in flame height. It seems that for carbon dioxide, the extinguishing concentration was relatively insensitive to such phenomena, although for nitrogen there was a small but definite increase in extinguishing concentration at the higher of the two air and agent flow rates studied. Under the “standard” conditions of 40 L min⁻¹ air plus the nitrogen flow rate, the measured extinguishing concentration of 33.7 \pm 0.5 volume % agreed closely with the ISO value of 33.6 volume %. Fixing the total flow rate at 40 L min⁻¹, however, led to a clear

reduction in the nitrogen extinguishing concentration. It should be noted that due to the relative inefficiency of nitrogen, the total flow rate under standard conditions is considerably higher than for carbon dioxide, which may explain the more pronounced effect.

Since it is well known that there is typically no extinguishing concentration plateau with respect to air flow rate for inert gases, some care is needed when fixing the combined air and agent flow rate to avoid recording misleading results.

COMBINED AIR AND AGENT TEMPERATURE

It is clear from data presented in Figure 3 that there is a significant dependence of extinguishing concentration upon the air and agent temperature for nitrogen or carbon dioxide. When conducting tests within the temperature boundaries specified by ISO 14520, the extinguishing concentrations increased by 4.6 ± 0.5 volume % for nitrogen and 3.0 ± 0.5 volume % for carbon dioxide, when moving from the lowest to the highest allowed temperature. This magnitude of discrepancy is significantly outside the limits of the experimental error (± 0.5 volume %) and must be considered to represent a genuine effect. Under ISO 14520, any extinguishing concentrations obtained within the allowed temperature range could be considered valid and reportable, despite the considerable potential variation. NFPA 2001 does not specify a desirable temperature range, so inert gas extinguishing concentrations reported under this protocol would need to be considered carefully in the absence of combined air and agent temperature data.

The dependence of extinguishing concentration upon air and agent temperature can be considered in terms of various physical properties of the gases. The integrated heat capacities for the air and agent mixtures between ambient and flame temperature can be calculated from literature data by evaluating the integral [6, 7]:

$$\int_{T_{\text{ambient}}}^{T_{\text{flame}}} C_p \, dT \quad (1)$$

In Equation (1), C_p is the heat capacity of the gas mixture. Assuming a limiting flame temperature in the range 1600 K [8] to 1800 K [9], it was found that the total integrated heat capacity of nitrogen and air mixtures at the extinguishing concentration decreased by around 1.4 % when the combined gas stream temperature was increased from 15 to 35 °C. For carbon dioxide, the integrated heat capacity of the gas stream at the flame extinguishing composition diminished by 0.3 % over the same temperature range.

Assuming ideal gas behaviour, simple calculations showed that the air and agent volume in the cup burner chimney increased by around 6 % on raising the temperature of the gas stream from 15 to 35 °C. The attendant decrease in the density (and increase in velocity) of the gas mixture would mean that the agent residence time in the flame would decrease, leading to an increase in the required extinguishing concentration. This effect would be consistent with the known dependence of inert gas extinguishing concentration upon air flow rate. It would seem, therefore, that the change in air and agent density may in fact be more significant than small changes in integrated heat capacity in terms of influencing the inert gas extinguishing concentration when the temperature is increased from 15 to 35 °C.

Other physical properties of the gases such as binary diffusion rate or thermal conductivity may also be influenced by temperature increases and therefore affect the observed extinguishing concentration.

Finally, the considerably enhanced fuel burning rates observed when the air and agent temperature was increased might be expected to contribute to greater flame stability and higher flame extinguishing concentrations.

RATE OF AGENT ADDITION

It is evident from the data presented in Figure 4 that differences in the rate of agent addition had a slight effect on the nitrogen extinguishing concentration, but no effect was observed for carbon dioxide outside experimental error. Interestingly, for nitrogen, the sudden addition method led to a relatively low extinguishing concentration, even though the trend had been for extinguishing concentration to increase with increasing rate of agent addition. It is thought that the initial turbulence due to a sudden increase in the total air and agent flow rate from 40 L min^{-1} to more than 50 L min^{-1} may have destabilised the flame and made it easier to extinguish [5]. The formation of a significant pre-mixed region in the flame upon sudden agent addition may be expected to lead to a higher extinguishing concentration, but this could be largely balanced by the observed flame lift-off contributing to a strained flame [10].

The mean fire out times at various agent addition rates were shorter for carbon dioxide and this may be due to the fact that the extinguishing concentration is lower than for nitrogen, so fewer incremental increases in agent concentration were needed.

FUEL LEVEL IN THE CUP

From the data presented in Figure 5, it is clear that the overall effect on nitrogen or carbon dioxide extinguishing concentrations of changing the fuel level in the cup was minimal. The slight increase in nitrogen concentration required when adjusting the fuel level through 2 mm is outside experimental error, but is nonetheless a small effect. Carbon dioxide concentrations were essentially unaffected by the fuel level, which is perhaps not surprising as it is a more effective fire extinguishing agent than nitrogen, making it more difficult to detect such a subtle effect. Previous work has indeed shown that reducing the fuel level to 2 mm below the lip had no appreciable effect on Halon extinguishing concentrations, although these agents are required in much lower quantities than the inert gases [5]. Despite these observations, it is worth pointing out that raising the fuel level from the chamfer to the lip results in an increase in surface area of around 16 %, which would lead to higher heat output and fuel consumption rates, as noted in the Results section. This effect may have been manifested in the slight increase in nitrogen extinguishing concentration observed on raising the fuel level in the cup.

Conducting tests with the fuel level significantly below the lip might be expected to provide a heat feedback route to the fuel via the steel, but this was not apparently a major factor in the light of the extinguishing concentration data obtained at the lowest fuel level.

It would be expected that the increased nitrogen extinguishing concentrations would be accompanied by fuel temperature increases. The opposite was found, suggesting that the fixed position fuel thermocouple was indicating a temperature gradient through the fuel rather than absolute measurements of fuel temperature at flame extinction for different fuel levels.

PRE-BURN PERIOD

It was interesting to note the insensitivity of extinguishing concentration to the length of the pre-burn period, since the burning rate of the fuel was observed to increase as the pre-burn was extended. The attendant increase in fuel temperature with longer pre-burn time would be expected to present a more challenging flame, although other workers have observed that maximum fuel burning rates typically occur within a few seconds of flame ignition [5]. Flame height analyses indicated that the flame had not reached its maximum size after 60 seconds and this short pre-burn period could be considered inappropriate since the flame is not fully stabilised within this time. The observations made in this study indicated that the pre-burn period (within a range of 60 to 120 seconds) was not a major influence on extinguishing concentration, although allowing a pre-burn of 5 minutes or longer [9] may have an impact due to the inevitable heating of the bulk fuel.

The cup material in this study was stainless steel as opposed to glass, which is used in many other cup burners. The thermal characteristics of the two materials differ and edge temperatures may be expected to reflect this and have some effect on the relative extinguishing concentrations. Despite this, a previous study compared glass and metal (brass) cup burners using nitrogen and carbon dioxide and found quite small differences in the extinguishing concentrations [11].

CONCLUSIONS

- The cup burner method has been shown to be generally sound, yielding repeatable extinguishing concentrations for inert gases as long as adherence to the detail of the published standards was maintained.
- Varying most parameters within the limits allowed by ISO 14520 or NFPA 2001 did not have a significant effect on measured extinguishing concentrations.
- A clear dependence of the nitrogen or carbon dioxide cup burner extinguishing concentration upon the temperature of the combined air and agent gas stream has, however, been demonstrated.
- Minor effects were more pronounced for nitrogen than carbon dioxide, possibly as nitrogen is a less efficient agent and small percentage changes in the extinguishing concentration were observed as larger absolute changes in the required quantity of nitrogen.

ACKNOWLEDGEMENTS

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