MEASUREMENT OF THE EXTINGUISHING CONCENTRATION OF GASEOUS FUELS USING THE CUP-BURNER APPARATUS*

Erdem A. Ural
Combustion Research Center
Fenwal Safety Systems
Holliston, MA 01746, USA

INTRODUCTION

A standardized cup-burncr test protocol will be incorporated into the NFPA and ISO standards for clean agents [1,2]. Part of this protocol is applicable to the testing of gaseous fuels. Section B.6.3 of the draft protocol requires that during tests, the fuel flow rate is adjusted to "attain **a** gas velocity nominally equal to the air velocity past the cup." This requirement is potentially dangerous to follow, because it unintentionally results in under-ventilated flames inside the cup burner. with the possibility of fuel accumulation in the vcntilation system or a secondary Ilamc attached over the top of the chimney.

DIFFICULTY OF APPLYING THE PROPOSED PROTOCOL TO GASEOUS FUELS

Section B.6.3 of the proposed protocol [1] suggests that the gaseous fuel flow rate be adjusted "to attain a gas velocity nominally equal to the air velocity past the cup.'' Since the fuel cup O.D. and the chimney I.D. are fixed, the equal velocity requirement fixes the ratio of volumetric (and molar for ideal gas) tlow rates of air and fuel, which is simply equal to the ratio of the cross-sectional area of the annulus to that of the fuel cup. This ratio is calculated as follows:

Original I.C.I. Apparatus:	6.05 moles of air/mole of fuel
Proposed Protocol Maximum:	8.65 moles of air/mole of fuel
Proposed Protocol Minimum:	6.17 moles of air/mole of fuel

On the other hand. a minimum amount of air is required by the fuel stoichiometry to create over-ventilated tlames that display a closed and elongated appearance. Under-ventilated flames are fan shaped and extend from the cup to the chimney.

The minimum air requirement depends on the fuel and can he calculated from the stoichiometry. For some typical gaseous fuels, the minimum air requirements are calculated as follows:

Methane:	9.57 moles of air/mole of fuel
Propane:	23.92 moles of air/mole of fuel
Butane:	31.10 moles of air/mole of fuel

Since the stoichiometric air requirement is larger than that allowed by Section B.6.3, the proposed protocol [1] unintentionally results in under-ventilated flames inside the apparatus, with the possibility of a secondary flame attached on top of the chimney. Therefore, an exploratory study was undertaken to develop recommendations for a revision of the proposed protocol.

EXPLORATORY STUDY

The cup-burner apparatus used in the study is one of the original cup-burner devices built by the I.C.I. The glass cup is lined with an electrical heating element, which allows testing of high flash point fuels. (Electrical heating was not utilized in any of the tests reported in this document.) Key dimensions listed below refer to Figure 1.

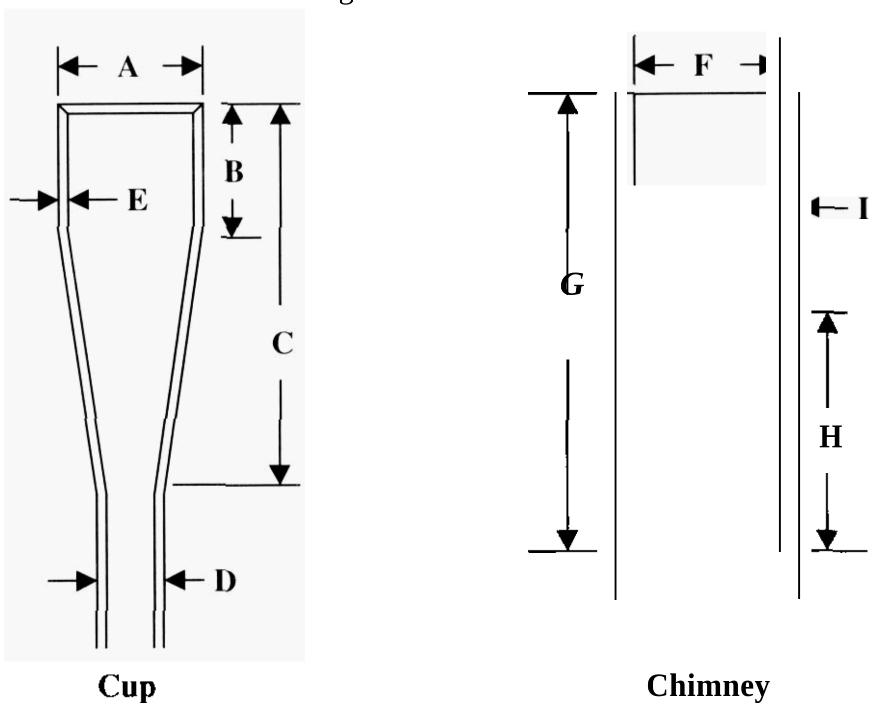


Figure 1. Nomenclature for the **key** dimensions of the cup-burner apparatus.

Cup

Cup outside diameter **(A):** 31.8 mm	Height (B): 25 mm
Taper height (C): 61 mm	Stem outside diameter (D): 12 mm
Wall thickness (E): 4.8 mm	Lip chamfer (bevel): 45 degrees

Location of Fuel Thermocouple below the top of the cup: 24 mm

Chimney

Inside diameter (F): 84 mm	Height (G): 532 mm
Cup placement (H): 230 mm	Wall thickness (I): 1.9 mm

A schematic diagram of the assembly is given in Figure 2. Air is supplied from a laboratory compressor. Therefore, oxygen concentration is always the atmospheric value of 20.9 vol.%. The extinguishing agent and air are mixed in the tubing downstream of the rotameters prior to entering the flow straightener (diffuser) section located at the bottom of the chimney. The diffuser section, which is designed to ensure a uniform distribution of air/extinguishant flow across the cross section of the chimney, is approximately 70 mm diameter, 76 mm tall, and is packed with 7.5 mm diameter glass spheres.

When testing liquid fuels. fuel level is maintained at the top of cup using a U-tube arrangement connected to a separatory funnel seen in Figure 2. The fuel level in the cup can be controlled accurately using a fine pitch screw mechanism.

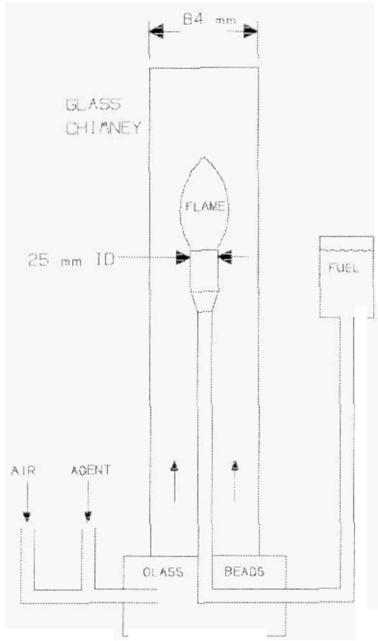


Figure 2. Schematics of the cup-burner assembly.

For the gaseous fuel tests, the cup is filled with sand to the top of the chamfer. Fuel is supplied through the stem of the cup using a rotameter calibrated with each test fuel. Filling the cup with sand requires some care to ensure an axisymmetric tlamc extending all the way out to the top of the chamfer.

Agent and air tlow rates are controlled and measured using calibrated rotameters. A calibrated gas analyzer is utilized to provide an independent measurement of the extinguishing agent concentration in air from a sample continuously drawn from the mixing tube upstream ofthe cup burner.

There was excellent agreement between the agent Concentration measured using the gas analyzer and the agent concentration calculated from the rotameter calibration curves. The exploratory test program was limited to methane and propane as the test fuel. while nitrogen and HFC-227ea were used as the extinguishnnt. The test matrix was designed to evaluate the cffects of air tlow rate and the fucl flow rate (or visible flame height) on the extinguishing concentration.

EFFECT OF FUEL FLOW RATE ON THE VISIBLE FLAME HEIGHT

These tests were performed at a fixed air flow rate of 40 slpm. No extinguishing agent was added. Since the measurement of the flame height using a ruler from outside the chimney is considered a somewhat subjective method, thesc tests were repeated by two different operators.

The results plotted in Figure 3 show a good agreement between the measurements obtained by the different operators. The air flow rate is 40 slpm. Heat release rates are calculated assuming the complete combustion of the metered fuel (which results in a volumetric combustion heat of 33.13 J/cm^3 for methane and 84.42 J/cm^3 for propane, at standard temperature and pressure).

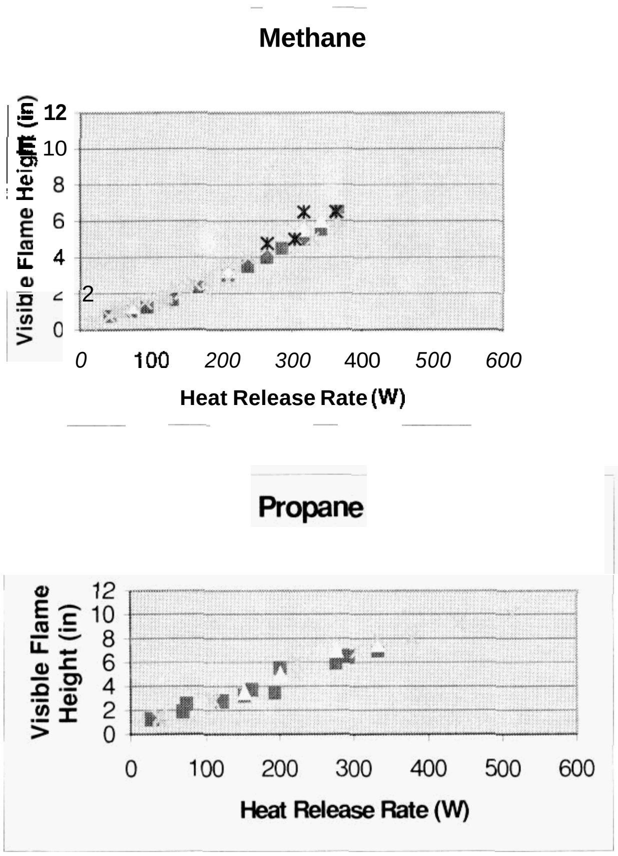
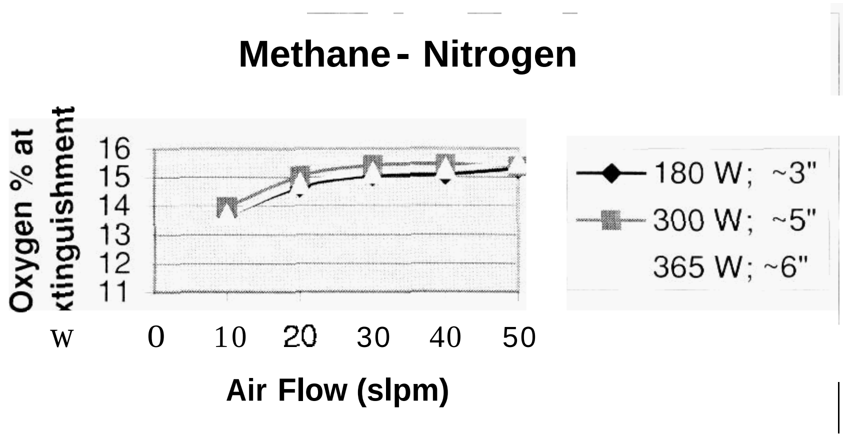


Figure 3. Recorded visible heights for methane and propane flames. Different symbols denote measurements taken by two different operators.

As expected from laminar diffusion flame theory, flame height is seen to be proportional to the heat release rate. This linear relationship allows one to use the parameters "visible flame height," "fuel release rate," and the "nominal heat release rate" interchangeably with the aid of single conversion constants. The use of the "visible flame height" parameter greatly simplifies the test protocol and minimizes the risk of operator or apparatus error due to incorrect calibration data fuel supply.

EFFECT OF AIR FLOW RATE ON THE EXTINGUISHING CONCENTRATION

A limited number of tests have been conducted to evaluate the effect of the air flow rate on the test results (Figure 4). The legends show the calculated heat release rate for complete combustion and the flame heights recorded prior to the introduction of the extinguishant. Extinguishing concentration measurements seem to be affected at low air flow rates.



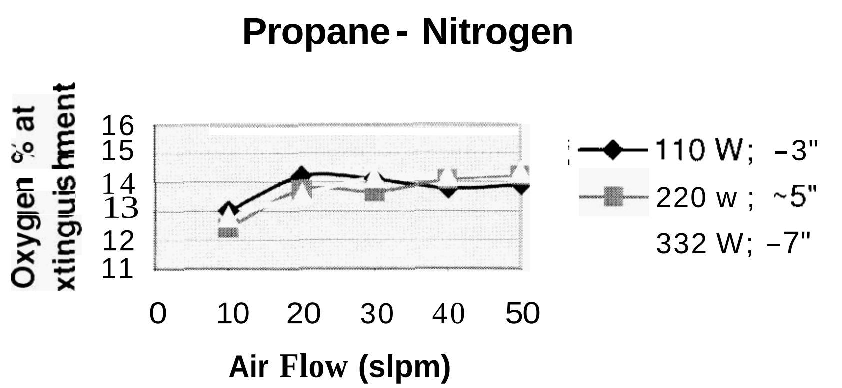


Figure 4. Effect of air tlow rate on extinguishing concentration. Each point represents a single test (no repeats).

To investigate the cause of this unexpected behavior. smoke generating wicks were used to visualize the tlow near the top (exit) of the chimney. Smoke movement revealed a secondary flow of downward fresh air drafts around the perimeter of the chimney cross section. Since the extinguishing concentration is measured upstream of the cup-burner apparatus, such downward drafts supplying fresh air to the flame from the top of the chimney can lead to erroneous test results. In fact, this downward draft is responsible for continuation of a diffusion flame even after the air supply is completely shut off.

Elimination of the fresh air supply from the chimney by placing a flow restriction on the top is not straightforward because of the pulsating nature of the flames at low air flow rates. The flow visualization study showed that the downward draft becomes intermittent as the flame is pulsating. There was no evidence of downward fresh air drafts for air flow rates of 30 **slpm** or more.

EFFECT OF FUEL FLOW RATE ON THE EXTINGUISHING CONCENTRATION

The majority of these tests were conducted at 40 slpm air flow rate. The results obtained using nitrogen are presented in Figure 5 as a function of the flame height in agent free air flow. Similar results for HFC-227ea can be found in Figure 6

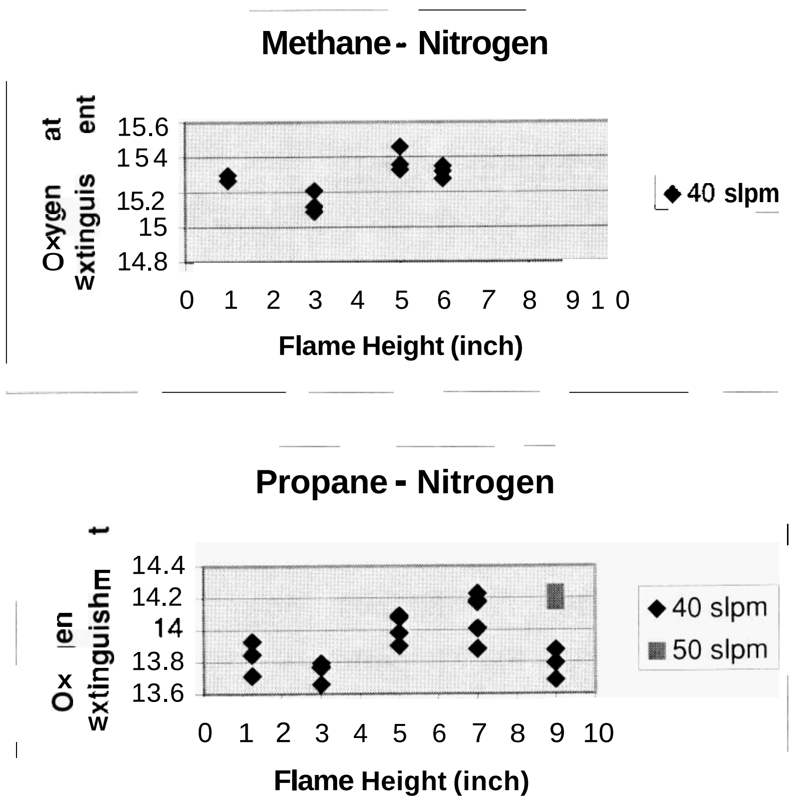
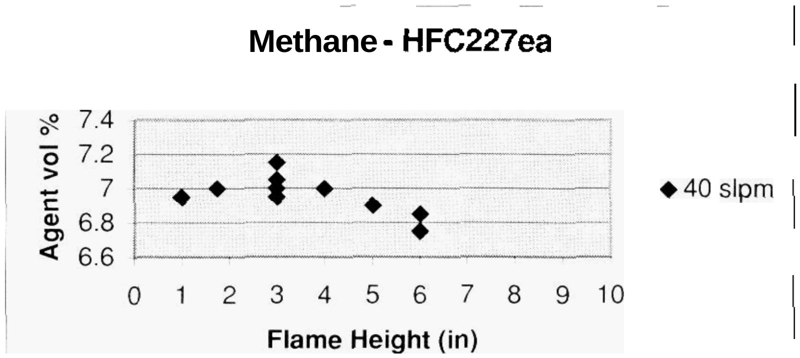


Figure 5. Effect of initial flame height on the extinguishing concentration.
Note: A 3 to 4 in tall flame is most difficult to extinguish.

For both agents and both fuels used in these limited number of tests, the agent demand for extinguishment appears to be largest for flames that are initially 3 to 4 in tall. Although the variation of the extinguishing concentration with flame height or fuel flow rate is relatively small, it is still significant when compared to the scatter of the experimental data.

An interesting observation is that the agent demand first increases, then decreases as the nominal fuel velocity (proportional to the flame height) is increased towards the nominal air velocity. Even at the maximum flame heights reported here, the nominal fuel velocity is only **a** small fraction of the air velocity. At a first glance this observation appears contradictory to the strong dependence of the agent demand on the strain rates observed in the Opposing Flow Diffusion Flame apparatus [3]. A possible reason for this apparent contradiction is offered (see DISCUSSION).



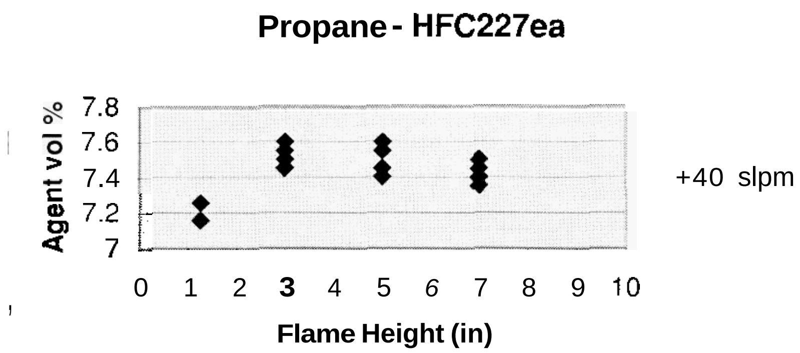


Figure 6. Effect of initial tlame height on tlic extinguishing concentration. Note: A flame that is initially 3 to 4 in tall is most difficult to extinguish.

Few experiments have been conductcd for initially 9 in tall propanc flames. Liquid fuels having high vapor pressurc (e.g., heptanc) produce flames tallcr than 9 in inside the cup-burner apparatus (Figure 5). When the air flow rate was set at 40 slpm, these tall flames were persistent and difficult to extinguish. At an oxygen concentration near 14.4 vol.%. the llame lifted approximately I **in** above the cup. as was observed immediately before the extinguishment in tests with shortcr flames. With the 9 in flame, however. the tlame did not extinguish near the **I** in lift-off. instead it persisted down to 13.8 vol.% oxygen. As the oxygen concentration is lowered below 14.4%, the flame lifted off higher and higher, and its appearance changed. Just before the cxtinguishment near 13.8%, the flame was lifted several inches (up *to* 6 in observed) above the cup, with a turbulent wispy appcarance and blue color.

The tests with 9 in tall flamc were repeated at 50 slpm of air flow (Figure 5). In this case, the extinguishment occurred around 14.2% oxygen. Appearance of the tlame just before the cxtinction was similar to that observed in tests with shorter initial flame heights. The excessive tlame lift-off observed near the extinguishment of tall flames **is** likely to be **a** peculiarity of the cup-burner apparatus due to its special tlame stabilizing flow geometry. It is practically impossible to envision a several inch lift-off from a I in diameter low momentum fuel release in an actual fire scenario.

DISCUSSION

The simplicity of the cup-burner apparatus makes it an ideal tool to evaluate the extinguishing capability of gaseous suppressants. This study showed that, despite its apparent simplicity, complicated secondary phenomena can take place inside the apparatus. Although the effects of the secondary phenomena seem remarkably small, selection of the test parameters with an understanding of these complicating effects is likely to improve the reproducibility of the test results.

Air and fuel supply rates are very important as they affect the flames through a number of different paths. Global stoichiometry during a test is governed by air and fuel supply rates. For a reliable operation, global stoichiometry of the cup burner needs to be quite lean.

Buoyancy of the combustion products generates locally high velocities. As a result, the flame starts necking inward at a small distance above the cup. The fuel and air supply rate data for the most difficult to extinguish ***3*** in flames were analyzed to determine the thickness of the innermost air layer around the cup, which is just necessary for complete combustion. The results show that the air burning the tip of the flame is coming from only **3.3** mm outside the cup for the methane flame, and 2.1 mm for the propane flame if a uniform air velocity profile is assumed.

The data show no sensitivity to the strain rate. This is an obvious advantage of the cup burner over the opposing flow diffusion flame apparatuses. The lack of sensitivity to the strain rate might be explained by the inward necking of the flame. The geometry of flow inside the cup-burner apparatus is ideal for the stabilization of detached flames above the cup.

Secondary air flow observed at low air flow rates was shown to affect the test results drastically. The temperature of the chimney glass can conceivably affect the secondary flow.

Finally, the visual appearances of the flame in the absence of the agent as well as immediately before the extinction can provide valuable clues and should be recorded as a part of the test data.

CONSIDERATIONS FOR LIQUID FUELS

When testing liquid fuels, the fuel release rate can not be controlled independently. The fuel release rate will depend on parameters such as fuel vapor pressure and evaporation enthalpy, surface temperature and temperature gradient, radiative heat release from the flame, distance between the flame and cup surface, and temperature of the chimney glass. The operator of the cup-burner apparatus can externally affect some of these parameters with the electrical current to the fuel heating element. fuel heating rate, the pre-burn duration, and the time spent at high agent concentrations prior to extinction.

The preceding remarks on gaseous fuels (see **DISCUSSION)** are applicable to the liquid fuels as well. Therefore, the heptane benchmark used for agent performance comparisons might not be the best choice from the cup-burner operational perspective because, in the absence of the agent, heptane flames are taller than 9 in. As the agent concentration is increased, the heat feedback to the fuel decreases and the flame height gets somewhat shortened due to a reduced evaporation rate. Therefore, the measured extinguishing concentration might depend on how fast or how slow the extinguishment is achieved.

PROCEDURE RECOMMENDED FOR GASEOUS FUEL TESTS

Based on the results of the exploratory study presented in this paper, the following test procedure appears appropriate:

1. Fix the air flow rate at 40 slpm.
2. Adjust fuel llow rate to obtain a visible flame height of 3 in.
3. Determine the extinguishing concentration.
4. Repeat steps 2 and 3 for larger and smaller flame heights until confident that the flame height requiring highest agent concentration is tested.
5. Make *a* note of those tests resulting in excessive flame lift-off as well as tests with unusual flame appearance. Even if these anomalies iire reproducible. the data might not he representative of the extinguishment capability in situations other than in the cup-burner apparatus.

ACKNOWLEDGMENT

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