

A PARAMETRIC STUDY OF THE EFFECT OF FIRE SOURCE ELEVATION IN A COMPARTMENT

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(ABSTRACT)

The objective of the present study was to acquire a better understanding of parameters controlling the species generation and transport from compartment fires. The experiments were performed in a half-scale ISO 9705 compartment and a 6.1 m long hallway connected in a head-on configuration. The buoyancy driven propane fire was provided by a burner and a continuous gaseous fuel supply system. All the measurements were obtained during the steady state of the fire. The ventilation conditions were fixed and three different fire source elevations were studied for heat release rates ranging from 20 kW to 150kW.

The species yields were obtained from performing detailed mapping measurements at the compartment and hallway exit planes. The measurements included local specie mole fractions of oxygen, carbon dioxide, carbon monoxide and unburned hydrocarbons. The local temperature and the local pressure (for local gas velocity calculations) were also measured. In addition, visual observations of the flow dynamic were performed through a window and the vents to give useful insights and lead to a better understanding of the combustion process.

The data obtained from the species generation study was analyzed using previously developed methods. The method based on equivalence ratio was presented and determined inappropriate for the present study where the global equivalence ratio was not equal to the plume equivalence ratio due to the complexity of the fire dynamic taking place. The method consisting of correlating the species yields based on the combustion

within the compartment as a function of a non dimensional heat release rate allowed qualitative conclusions to be made. The non-dimensional heat release rate was based on the fuel load and the geometric parameters of the compartment. This methodology revealed similarities in the species production between the three fire source elevations investigated. A correlation of the data was obtained based on experimental data.

The transport of species to remote locations was studied for the three fire source elevations and fixed ventilation conditions. Species mole fractions and yields were obtained at the compartment exit plane (compartment/hallway interface) and at the hallway exit plane. The results were compared for various heat release rates and showed differences for some scenarios attributed to mixing along the hallway and oxidation reactions outside the compartment.

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TABLE OF CONTENT

ABSTRACT	ii
ACKNOWLEDGEMENT	iv
LIST OF FIGURES	viii
LIST OF TABLES	xiii
NOMENCLATURE	xv
Chapter 1 – INTRODUCTION	1
1.1 INTRODUCTION	1
1.2 MOTIVATION	1
1.2.1 Carbon Monoxide	1
1.2.2 Structure Fires Statistics	2
1.3 PREVIOUS WORK	4
1.3.1 Hood Experiments	4
1.3.2 Scaled-Compartment Experiments	7
1.3.2.1 Ideal Two-Layer Compartment	7
1.3.2.2 Compartment With Prototypical Building Features	10
1.4 TRANSPORT OF SPECIES TO ADJACENT SPACES	16
1.4.1 Transport to Unconfined Adjacent Spaces	16
1.4.2 Transport to Confined Adjacent Spaces, Hallway studies	16
1.5 OBJECTIVES OF RESEARCH	20
Chapter 2 – EXPERIMENTAL APPARATUS AND PROCEDURES	21
2.1 EXPERIMENTAL APPARATUS	21
2.1.1 Experimental Facilities	21
2.1.1.1 Scaled Test Compartment and Hallway	21
2.1.1.2 Concrete Enclosure	23
2.1.1.3 Exhaust Hood	24
2.1.2 Continuous Fuel Line and Elevated Burner	25
2.1.3 Data Acquisition	27

2.1.3.1 Local Measurements	27
2.1.3.2 Temperature Measurements	27
2.1.3.3 Fire Gases Velocity Measurements	30
2.1.3.4 Gas Sampling	31
2.1.4 Sampling Rakes	33
2.1.5 Gas Analysis	35
2.1.5.1 CO and CO ₂ Gas Analyzer	35
2.1.5.2 O ₂ Gas Analyzer	36
2.1.5.3 Unburned Hydrocarbon Measurements	37
2.1.6 Data Acquisition System	38
2.2 EXPERIMENTAL PROCEDURE	39
2.2.1 Equipment Calibration	39
2.2.2 Cleaning of Filters and Rakes	39
2.2.3 Leak Testing of Sampling Line and Sampling Rakes	39
2.2.4 Ignition of the Fire	40
2.2.5 Test Procedure	40
2.2.5.1 Doorway Mapping	41
2.2.5.2 Visual Observation	42
2.3 DATA REDUCTION CALCULATIONS AND PROCEDURES	43
2.3.1 Local Average Properties	43
2.3.1.1 Local Wet Species Mole Fractions	43
2.3.1.2 Local Wet N ₂ Mole Fraction	45
2.3.1.3 Local Temperature	45
2.3.1.4 Local Velocity	46
2.3.2 Neutral Plane Location	46
2.3.3 Integrated Mass Flow Rates through the Doorways	47
2.3.4 Integrated Species Mass Fractions	48
2.3.5 Inflow Mass Flow Rates – Mass Balance	49
2.3.6 Species Yields	50
2.3.7 Ideal Heat Release Rate	52

Chapter 3 – BURNER ELEVATION PARAMETRIC STUDY	53
3.1 MOTIVATION FOR THE BURNER ELEVATION STUDY	53
3.2 PRESENTATION OF THE RESULTS	58
3.2.1 Test Matrix	58
3.2.2 Air Entrained into the Compartment	59
3.2.3 Integrated Average Species Mole Fractions vs. the Ideal Heat Release Rate	61
3.2.4 Species Yields vs. the Ideal Heat Release Rate	63
3.2.5 Species Yields vs. the Global Equivalence Ratio	72
3.2.6 Species Yields vs. the Non Dimensional Heat Release Rate	74
3.3 CORRELATION DEVELOPMENT	83
 Chapter 4 – CARBON MONOXIDE TRANSPORT STUDY	 87
4.1 MOTIVATION FOR TRANSPORT STUDY	87
4.2 PRESENTATION OF THE RESULTS	88
4.2.1 Transport Study Test Matrix	88
4.2.2 Carbon Monoxide Yields Vs. Ideal Heat Release Rate at Both Locations	89
4.3 HALLWAY VENTILATION SIZE EFFECTS ON THE FLOW DYNAMIC	94
4.3.1 Hallway Ventilation Size Effects on the Air Entrainment	95
4.3.2 Hallway Ventilation Size Effects on the Carbon Monoxide Transport	97
 Chapter 5 – SUMMURY AND CONCLUSIONS	 100
5.1 INTRODUCTION	100
5.2 STUDY OF SPECIES GENERATION IN AN ATTACHED COMPARTMENT	100
5.3 CARBON MONOXIDE TRANSPORT STUDY SUMMARY	103
 Chapter 6 – RECOMMENDATIONS FOR FUTURE WORK	 105
 REFERENCES	 106
APPENDIX A – UNCERTAINTIES CALCULATIONS	112
APPENDIX B – RAW DATA FILES	124

LIST OF FIGURES

FIGURES	PAGE
Figure 1-1: Schematic of the two-layer system created in the hood experiments of Beyler.(Adapted from Gottuk <i>et al.</i> 2002)	4
Figure 1-2: Unnormalized carbon monoxide yields as a function of the plume equivalence ratio for gaseous, liquid and solid fuels. Results obtained by Beyler [1983] from hood experiments. (Taken from Gottuk <i>et al.</i> 2002)	5
Figure 1-3: Schematic of an Ideal Two-Layer Compartment.	8
Figure 1-4: Unnormalized carbon monoxide yields as a function of the global equivalence ratio based on the work by Gottuk [1992] compared with <i>n</i> -hexane data from Beyler [1983]. (Taken from Wieczorek [2002])	9
Figure 1-5: Schematic of a compartment with prototypical building features.	10
Figure 1-6: Carbon monoxide yields as a function of the equivalence ratio and doorway width based on the work of Wieczorek [2002] compared with data from Gottuk [1992], Beyler [1983], and Bryner <i>et al.</i> [1994] in addition to correlations from Gottuk [1992] and Beyler [1983]. (Taken from Wieczorek [2002])	11
Figure 1-7: Carbon monoxide yield (based on combustion within the compartment) as a function of the non dimensional heat release rate. (Taken from Wieczorek [2002])	14
Figure 1-8: Carbon Monoxide yields (based on combustion within the compartment) as a function of $\tilde{Q}$ along with a curve fit to the data.	15
Figure 1-9: Ideal two-layer compartment / Hallway in head on configuration for species transport study conducted by Ewens [1994]. (Image taken from Gottuk and Lattimer [2002])	17
Figure 1-10: Ideal two-layer compartment / Hallway in side-on configuration for species transport study conducted by Lattimer [1996]. (Image taken from Gottuk and Lattimer [2002])	18
Figure 1-11: Half-scale ISO 9705 Compartment / Hallway in head-on configuration for species transport study conducted by Wieczorek [2002]. (Image taken from Wieczorek [2002])	19

Figure 2-1:	Half-Scaled ISO 9705 Compartment, with variable height fire source.	21
Figure 2-2:	Half-scaled ISO 9705 Compartment with hallway in a head-on configuration	22
Figure 2-3:	(a) Picture of the enclosure, (b) Top view and east view of concrete enclosure. (Image adopted from Wieczorek [2002] and modified)	23
Figure 2-4:	Exhaust system.	24
Figure 2-5:	(a) Schematic of burner, (b) Burner on the adjustable stand.	26
Figure 2-6:	Schematic of the continuous gaseous fuel supply system.	26
Figure 2-7:	(a) Picture of the fuel line, (b) Mass flow meter.	27
Figure 2-8:	(a) Compartment thermocouple rake, (b) Thermocouple rake on the compartment sampling rake.	28
Figure 2-9:	(a) Drawing of bi-directional Pitot probe, (b) Pressure transducers.	30
Figure 2-10:	Signal conversion for pressure transducers; (a) Range: $\pm 0.1''$ H ₂ O and (b) Range: $\pm 0.25''$ H ₂ O.	30
Figure 2-11:	Series of filters for sampling line.	32
Figure 2-12:	Schematic of the gas route from sampling rake to analyzers.	33
Figure 2-13:	CAD drawing of the tip of a sampling probe.	33
Figure 2-14:	Picture of the compartment door sampling rake.	34
Figure 2-15:	Picture of the hallway end door sampling rake.	34
Figure 2-16:	Signal conversion from volts to mole fraction for (a) CO (0%-1%), (b) CO (0%-5%) and (c) CO ₂ (0%-25%).	35
Figure 2-17:	Signal conversion from volts to mole fraction for O ₂ (0%-22%).	36
Figure 2-18:	Schematic of Flame Ionization Detector.	37
Figure 2-19:	(a) Schematic of the Compartment sampling rake, (b) Measurement grid for the compartment baseline doorway.	41
Figure 2-20:	(a) Schematic of the Hallway end sampling rake b) Measurement grid for hallway-exit narrow doorway.	42
Figure 2-21:	Diagram for local properties calculations. (subscripts <i>i</i> and <i>j</i> refer to the location on the grid of the sampling point)	43

Figure 2-22:	Different cases of velocity profiles at a fixed w/W location for the compartment doorway (a) if $V7 < 0$, (b) if $V7 > 0$ and (c) the hallway doorway.	46
Figure 2-23:	Diagram of the calculations (subscripts i and j refer to the location on the grid of the sampling point, Superscript n refers to the specie considered).	50
Figure 3-1:	Representation of the fire dynamic for four $\tilde{Q}$ conditions (a) $\tilde{Q} < 1.0$ with fire below upper layer, (b) $\tilde{Q} < 1.0$, (c) $\tilde{Q} = 1.0$, (d) $1.25 < \tilde{Q} < 3.5$.	54
Figure 3-2:	Flame structure at the compartment/hallway interface for a sliver doorway for ideal heat release rate, $\dot{Q}_{ideal} = 130$ (kW) (Picture taken from Wieckzorek [2003])	56
Figure 3-3:	Schematic of the scenario for minimum internal burning	57
Figure 3-4:	Air entrainment mass flow rate through the compartment doorway as a function of the ideal heat release rate $\dot{Q}_{ideal}$.	61
Figure 3-5:	Integrated average carbon monoxide mole fractions (%) as a function of the ideal heat release rate, $\dot{Q}_{ideal}$ (kW).	62
Figure 3-6:	Integrated average carbon dioxide mole fractions (%) as a function of the ideal heat release rate, $\dot{Q}_{ideal}$ (kW).	62
Figure 3-7:	Integrated average depleted oxygen mole fractions (%) as a function of the ideal heat release rate, $\dot{Q}_{ideal}$ (kW).	63
Figure 3-8:	Heat Release Rate based on the measured oxygen depletion versus the Ideal Heat Release Rate.	67
Figure 3-9:	Carbon Monoxide species yield as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW).	68
Figure 3-10:	Normalized carbon dioxide species yield as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW).	68
Figure 3-11:	Normalized oxygen species yield as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW).	69
Figure 3-12:	Schematic representation of the fire dynamic for three burner elevations at a fixed ideal heat release rate (47 kW), (a) $h/H_{Door} = 12.5\%$, (b) $h/H_{Door} = 50\%$ and (c) $h/H_{Door} = 75\%$.	70

Figure 3-13:	Carbon Monoxide species yield as a function of the global equivalence ratio ϕ .	72
Figure 3-14:	Normalized carbon dioxide species yield as a function of the global equivalence ratio ϕ .	73
Figure 3-15:	Normalized oxygen species yield as a function of the global equivalence ratio ϕ .	73
Figure 3-16:	Pictures of the limit cases through the glass side window. (a) Flame extension for the burner elevation $h/H_{Door} = 75\%$, (b) Hot soot glowing for the burner elevation $h/H_{Door} = 50\%$.	74
Figure 3-17:	Schematic representation of the fire scenario for different values of ideal heat release rates for the burner elevation $h/H_{Door} = 12.5\%$. (a) $\hat{Q} < 1$, (b) $\hat{Q} = 1$ and (c) $\hat{Q} > 1$.	77
Figure 3-18:	Schematic representation of the fire scenario for different values of ideal heat release rates for the burner elevation $h/H_{Door} = 50\%$. (a) $\hat{Q} < 1$, (b) $\hat{Q} = 1$ and (c) $\hat{Q} > 1$.	78
Figure 3-19:	Schematic representation of the fire scenario for different values of ideal heat release rates for the burner elevation $h/H_{Door} = 75\%$. (a) $\hat{Q} < 1$, (b) $\hat{Q} = 1$, (c) $\hat{Q} > 1$.	79
Figure 3-20:	Carbon Monoxide species yield as a function of the non dimensional heat release rate $\hat{Q}$.	81
Figure 3-21:	Normalized carbon dioxide species yield as a function of the non dimensional heat release rate $\hat{Q}$.	81
Figure 3-22:	Normalized oxygen species yield as a function of the non dimensional heat release rate $\hat{Q}$.	82
Figure 3-23:	Normalized carbon monoxide species yield as a function of the non dimensional heat release rate $\hat{Q}$.	83
Figure 3-24:	Non dimensional carbon monoxide species yield as a function of the non dimensional heat release rate $\hat{Q}$ along with a curve fit to the data.	84
Figure 3-25:	Carbon monoxide species yield as a function of the non dimensional heat release rate $\hat{Q}$ along with a curve fit to the data.	85

Figure 3-26:	Normalized carbon dioxide species yield as a function of the non dimensional heat release rate $\hat{Q}$ along with the correlation obtained for the normalized CO ₂ yield applied to each configuration.	86
Figure 4-1:	Carbon Monoxide species yield (based on the fuel burning inside the compartment) at the compartment doorway ($x = 0$ m) and at the hallway doorway ($x = 6.1$ m) as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW) for $h/H_{Door} = 12.5$ %.	89
Figure 4-2:	Carbon Monoxide species yield (based on the fuel burning inside the compartment) at the compartment doorway ($x = 0$ m) and at the hallway doorway ($x = 6.1$ m) as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW) for the 50 % burner elevation.	90
Figure 4-3:	Carbon Monoxide species yield (based on the total amount of fuel) at the compartment doorway ($x = 0$ m) and at the hallway doorway ($x = 6.1$ m) as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW) for the 75 % burner elevation.	91
Figure 4-4:	Schematic of a scenario for $h/H_{Door} = 75$ % prior to external burning.	92
Figure 4-5:	Schematic of a scenario for $h/H_{Door} = 75$ % with sustained external burning.	93
Figure 4-6:	Schematic of a scenario for $h/H_{Door} = 75$ % with minimum fuel burning within the compartment.	93
Figure 4-7:	Picture of the sustained external burning with the burner at $h/H_{Door} = 75$ % and an ideal heat release rate of 52 kW.	94
Figure 4-8:	Air entrainment mass flow rate through the compartment doorway as a function of the ideal heat release rate $\dot{Q}_{ideal}$.	95
Figure 4-9:	Air entrainment mass flow rate through the hallway doorway as a function of the ideal heat release rate $\dot{Q}_{ideal}$.	96
Figure 4-10:	Compartment doorway species mole fractions mapping for a heat release rate of 62kW and a burner elevation $h/H_{Door} = 75$ %. (a) CO, (b) CO ₂ , (c) O ₂ and (d) UHC.	97
Figure 4-11:	Hallway doorway species mole fractions mapping for a heat release rate of 62kW and a burner elevation $h/H_{Door} = 75$ %.(a) CO, (b) CO ₂ , (c) O ₂ and (d) UHC	98

LIST OF TABLES

TABLES	PAGE
Table 1-1: Carbon monoxide effects on humans. (NFPA 2000)	2
Table 1-2: $\dot{Q}_{\text{Flame Extensions}}$ for the three doorways.	13
Table 2-1: Conversion coefficients from voltage reading to temperature for type K thermocouples.	29
Table 2-2: Conversion coefficients for pressure transducers.	31
Table 2-3: Conversion factors from volts to mole fraction for CO / CO ₂ gas analyzer.	36
Table 3-1: Surface area of the openings.	57
Table 3-2: Burner elevation study test matrix.	59
Table 3-3: Maximum air entrainment through the doorways.	60
Table 3-4: $\dot{Q}_{\text{Flame Extensions}}$ observed for each burner elevations.	76
Table 3-5: Species yields and calculated $\hat{Q}$.	80
Table 3-6: Maximum CO yield for each burner elevation configuration at $\hat{Q}=1$.	82
Table 4-1: Transport study test matrix.	88
Table A-1: List of equipment used and possible sources of uncertainties for each type of measurement performed for the present study.	112
Table A-2: Uncertainties due to the gas analyzers associated with dry species mole fraction measured.	113
Table A-3: Estimated uncertainty in dry species mole fraction measurements.	113
Table A-4: List of the direct measurements performed and the full-scale value and their associated estimated uncertainty.	115
Table A-5: Uncertainties associated to the wet species mole fraction calculation	117

Table A-6:	Estimated Uncertainties in Species Density.	120
Table A-7:	Estimated uncertainties in species density x velocity.	122
Table A-8:	Estimated uncertainties in species mass flow rates.	122
Table A-9:	Estimated uncertainties in species yields.	123

NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
A	area of the ventilation opening	m^2
a	coefficient	
b	coefficient	
c	coefficient	
d	coefficient	
D	diameter of the burner	m
dA	differential area	m^2
dh	differential height	m
dw	differential length	m
f^n	normalized yield of specie n	
factor	conversion factor	
H	height of the compartment	m
H_{Door}	height of the ventilation opening (doorway)	m
h	height location (referenced to the floor)	m
h_{NP}	neutral plane height	m
MW^{mix}	molecular weight of the mixture	$kg/kmol$
MW^n	molecular weight of specie n	$kg/kmol$
MW_{air}	molecular weight of air	$kg/kmol$
$\dot{m}_{out}^n$	mass flow rate of specie n	kg/s
$\dot{m}_{out}$	total mass flow rate of combustion gases	kg/s
$\dot{m}_{in,Bal}$	mass flow rate of air obtained from mass balance	kg/s
P_{atm}	Atmospheric pressure	
$\dot{Q}_{ideal}$	ideal heat release rate	kW
$\dot{Q}_{comp}$	heat release rate within the compartment	kW
$\dot{Q}_{MaxConfig}$	maximum ideal heat release rate before unsteadiness	kW

$\dot{Q}_{\text{Flame Extensions}}$	ideal heat release rate required for flame extensions to reach the top of the doorway	kW
$\hat{Q}$	non dimensional heat release rate	
$\tilde{Q}$	non dimensional heat release rate (Wieczorek [2003])	
R_u	universal gas constant	J/(mol K)
T	temperature	°C, °K
Volt	voltage reading	mV
V	velocity	m/s
$\dot{V}$	volumetric flow rate	m ³ /s
W	width of the ventilation opening (doorway)	m
w	width location (referenced to the left side of the doorway)	m
X_{wet}^n	wet mole fraction of species n	%
X_{dry}^n, X^n	dry mole fraction of species n	%
Y^n	yield of species n	g/g _{fuel}
Y_{theory}^n	maximum yields of species n based on stoichiometry	g/g _{fuel}
y^n	mass fraction of species n	
$\bar{y}^n$	integrated average mass fraction of species n	

Greek

ΔH_c	heat of combustion based on fuel	
$\Delta H_{c,ox}$	heat of combustion based on the oxidant	
ΔP	pressure difference	Pa
ρ	local gas density	kg/m ³
ρ^n	partial density of specie n	kg/m ³
ϕ	global equivalence ratio	
ϕ_p	plume equivalence ratio	
ϕ_{UL}	upper layer equivalence ratio	
χ	combustion efficiency	

Subscripts

CO	carbon monoxide
CO ₂	carbon dioxide
H ₂ O	Water
in	flowing in the compartment through the bottom region of the doorway
out	flowing out of the compartment through the top region of the doorway
O ₂	oxygen
s	stoichiometry
scrubbed	scrubbed gas (cleaned from combustion products)
UHC	unburned hydrocarbon

CHAPTER 1 - INTRODUCTION

1.1 INTRODUCTION

This chapter introduces the topic of this project and its main objectives. Year after year, statistics have shown that fires in residential and public buildings are disastrous. Causing the death of many, and resulting in enormous property loss, accidental structure fires are of a great concern to our society. More than the fire itself, carbon monoxide (CO) poisoning has been shown to be the primary cause of death from fires occurring in many occupancies. Previous research on carbon monoxide formation and the developed methodologies for its prediction are discussed in this chapter. Based on this discussion, the foundations and the objectives of the present study are presented.

1.2 MOTIVATION

1.2.1 Carbon Monoxide

Although not the only product of incomplete combustion formed in enclosure fires, CO has been shown to be the primary toxicant formed in such scenarios. [Gann *et al.* 1994] The study of its formation has therefore been the main focus of this research.

Carbon monoxide is very toxic to humans and inhaling it results in the reduction of the blood's capacity to carry oxygen. Hemoglobin in the blood has a preference for carbon monoxide that is 3000 times greater than that for oxygen. [Hartman *et al.* 1997] Loss of consciousness, asphyxiation and ultimately death are the effects of the presence of carbon monoxide in the blood. [Pon *et al.* 2001] The physiological effects of different carbon monoxide levels for humans related to exposure time are listed in Table 1-1. [NFPA 2000]

Table 1-1: Carbon Monoxide Effects on Humans (NFPA 2000)

Level of CO in air	Physiological Effect on Humans
50 ppm	Threshold limit value for no adverse effects
200 ppm	Possible mild headache after 2-3 hours
400 ppm	Headache and nausea after 1-2 hours
800 ppm	Headache, nausea and dizziness after 45 minutes; possible loss of consciousness after 2 hours
1000 ppm (0.1%)	Loss of consciousness after 1 hour
1600 ppm (0.16%)	Headache, nausea and dizziness after 20 minutes
3200 ppm (0.32%)	Loss of consciousness after 30 minutes
6400 ppm (0.64%)	Headache, nausea and dizziness after 1-2 minutes; Loss of consciousness and possible death after 10-15 minutes
12800 ppm (1.28%)	Immediate physiological effects; Loss of consciousness and danger of death after 1-3 minutes

1.2.2 Structure Fires Statistics

Hall [2003] reported 519,500 fires occurring in structures in 2003, an increase of 0.1% compared to 2002. Residential fires represent 77% of all structure fires. Accidental fire in densely populated places can be disastrous. In 2003, the number of death in homes, 3,925 civilians, increased by 17.6% compared to the preceding year reversing a decreasing trend.

More than the fire itself, carbon monoxide inhalation has been reported to be the most common cause of death in building fires over the past decades. Hall [1997] reported that 75% of all deaths in building fires were caused by inhalation of toxic gases and that 66% of all deaths were attributed to carbon monoxide inhalation.

Fires within houses are usually under-ventilated due to the presence of large amount of combustible material and the limited amount of ventilation. High levels of carbon monoxide are generated in such instances and are transported to adjacent spaces very quickly. Most of the injuries and deaths caused by carbon monoxide inhalation occurred at locations remote from the fire. High density residential buildings, such as nursing homes or dormitories, represent a real danger to their occupants in the case of a

fire. The following description of a fire occurring in a nursing home was taken from Lattimer [1996].

On October 5, 1989 at the Hillhaven Nursing Home in Norfolk, Virginia, a fire in a patient's room resulted in the death of 13 people. Each victim died of carbon monoxide poisoning with 12 of the victims found in a room or position down the hallway from the room containing the fire. Twenty-three patients resided along the wing containing the burning room, 9 of the victims were found in rooms on the opposite side of the hallway from the burning room while only one victim was found on the burning room side of the hallway. This was attributed to a wind from the south causing a draft, which drove the toxic gases across the hallway into the victim's rooms.

Due to the inevitable increase in population size and its aging, the number of nursing homes is growing every year. For the safety of their occupants, a better understanding of the parameters prevailing in a building fire is required.

1.3 PREVIOUS WORK

1.3.1 Hood Experiments

The toxic species generation from a buoyant diffusion flame has been the subject of many experimental investigations. From these studies, it was determined that the levels of toxic species generated from such flames are a complex function of the ventilation condition and the properties of the fuel and the oxidant. The foundations for this field of research were established by Beyler [1983, 1986] who performed a series of hood experiments in the open, Figure 1-1. These experiments were designed to simulate a two-layer compartment fire and study the upper layer of combustion products.

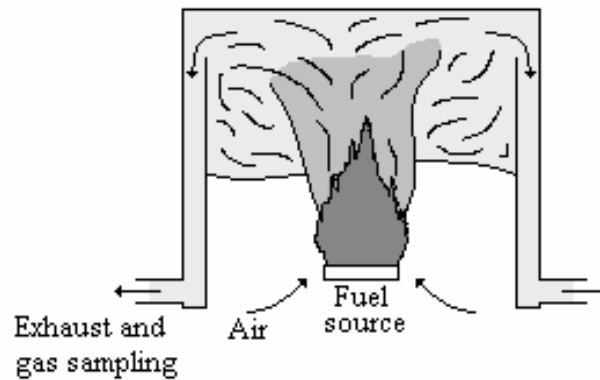


Figure 1-1: Schematic of the two-layer system created in the hood experiments of Beyler (Adapted from Gottuk *et al.* 2002)

Beyler [1983] was the first to introduce the possibility to correlate the combustion products to a parameter based on the fuel-to-air ratio. The production rate (and species yield) of the major species had to be assumed constant and thus insensitive to the unsteadiness of a diffusion flame. The determination of a steady state period was required for this analysis. Beyler [1983] proposed the Global Equivalence Ratio (GER, ϕ) which for his experiments was equal to the Plume Equivalence Ratio (PER, ϕ_p) since all the air was entrained through the fire plume.

The equivalence ratio is defined by Equation 1-1 and is the ratio of the measured fuel-to-air mass flow rate ratio to the stoichiometric fuel-to-air mass flow rate ratio. This equivalence ratio indicates if the fire is fuel rich or fuel lean compared to stoichiometric proportions.

$$\phi = \frac{\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air}}} \right)}{\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air}}} \right)_s} \quad (1-1)$$

Beyler's results of carbon monoxide yields for gaseous, liquid and solid fuels are presented as a function of ϕ_p in Figure 1-2.

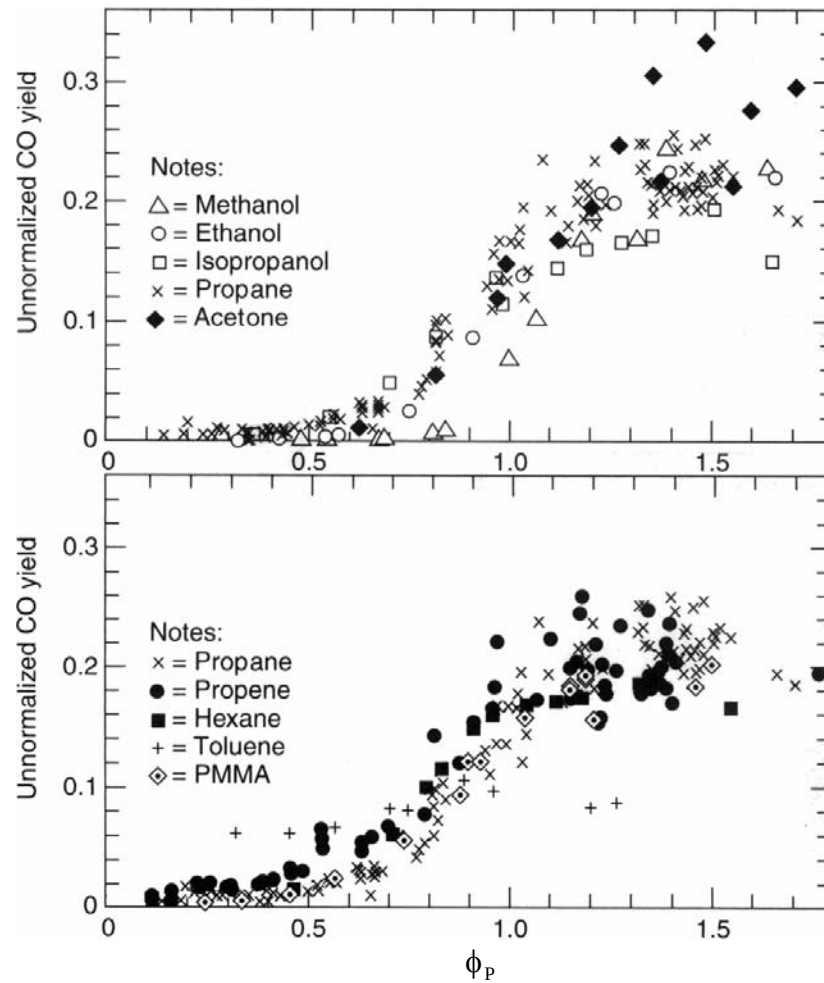


Figure 1-2: Unnormalized carbon monoxide yields as a function of the plume equivalence ratio for gaseous, liquid and solid fuels. Results obtained by Beyler [1983] from hood experiments. (Taken from Gottuk *et al.* 2002)

Beyler [1983] concluded that the major combustion species can be correlated in terms of an equivalence ratio. Beyler [1983] also reported a relatively constant production of CO at low PER ($\phi_p < 0.7$) and high PER ($\phi_p > 1.2$) and a considerable increase in CO production during the transition from fuel lean to fuel rich conditions ($0.7 < \phi_p < 1.2$).

Similar hood experiments were performed by other researchers. Toner et al. [1987] and Zukoski et al. [1985] studied methane fires under a 1.2 m cubic insulated collection hood and reported their data to correlate well to the plume equivalence ratio, ϕ_p . Their correlation was qualitatively similar to the one obtained by Beyler [1983].

Later, Zukoski, Morehart, et al. [1990] used the same apparatus with a slightly larger non insulated collection hood (a 1.8 m square by 1.2 m high) and performed similar tests. The fuel mass flow rate was kept constant and the upper layer equivalence ratio ϕ_{UL} was varied by injecting air into the upper layer at a measured rate. For each ϕ_{UL} investigated, the sampling began when the upper layer thickness was observed constant. Once again, the results were qualitatively similar, however slightly higher levels of CO were observed for under ventilated fires ($\phi_{UL} > 1$). Morehart [1990] concluded that it was the result of lower upper-layer gas temperatures, 120 K to 200 K lower than Toner et al., due to the larger non insulated collection hood. Morehart [1990] studied the effects of upper layer temperature on the products of combustion by keeping ϕ_{UL} constant and simply varying the insulation of the collection hood. As the upper-layer temperature increased, Morehart [1990] observed more products of complete combustion (i.e., CO₂ and H₂O) and more CO. Indeed, more fuel was being consumed and the upper layer oxygen mass fraction was considerably lower.

From these studies, the following conclusions were drawn for hood experiments:

- A steady state period can be assumed. During this steady state period, production and consumption rates of major species can be considered constant regardless of the the flame structure.

- A meaningful fuel-to-air ratio, or equivalence ratio, can be used to correlate the levels of species produced (i.e., CO, CO₂, O₂ and Unburned Hydrocarbons) by buoyancy driven fires under a collection hood.
- A relatively constant production of CO at low equivalence ratio ($\phi < 0.7$) and high equivalence ratio ($\phi > 1.2$) is observed. During the transition from fuel lean to fuel rich conditions ($0.7 < \phi < 1.2$) a considerable increase in CO production occurs.
- The combustion process and the resulting products are dependant on the upper layer temperature. The upper layer temperature depends on the properties and insulation of the walls containing it (i.e., the collection hood).

1.3.2 Scaled-Compartment Experiments

The species level dependency to the upper layer temperature required the test apparatus to be more representative of an actual room or compartment. Indeed, a lot of the radiation from the fire was lost to the surroundings when the fire was in the open under a collection hood. Enclosing the fire increased the upper layer temperature modifying the combustion process. In addition, ceiling jet flames and wall jet flames, not present in the hood experiments, also contributed to changes in the dynamic of the system.

1.3.2.1 Ideal Two-Layer Compartment

Pitts [1994] and Gottuk [1992] extended the equivalence ratio methodology to scaled-compartment fires. Gottuk [1992] performed experiments on liquid n-hexane pool fires in an ideal two-layer system, Figure 1-3. The air was entrained via a duct into a plenum around the burner. The combustion gases were exhausted through a window. The air entrainment and the exhaust gases being separated facilitated the measurement of the mass flow rates.

After investigating the temperature and the gas composition at several locations within the upper layer, Gottuk [1992] concluded that the upper layer was well mixed and a single point measurement was sufficient to represent each case.

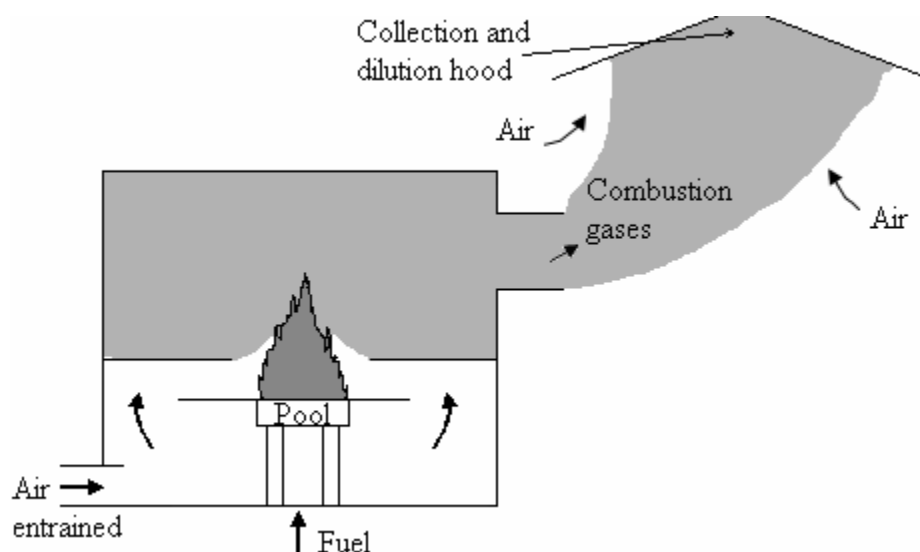


Figure 1-3: Schematic of an Ideal Two-Layer Compartment.

Very similar to the open hood experiment, the air was entrained into the fire from all around the burner. The equivalence ratio methodology was expected to apply to the system. For this ideal two-layer system, the global equivalence ratio was equal to the plume equivalence ratio since all the air entrained through the duct was entrained into the fire plume (i.e, Conservation of mass).

Although the data obtained by Gottuk showed similarities with the data obtained by Beyler [1983] significant quantitative differences were observed, see Figure 1-4. These discrepancies, for equivalence ratios ranging from 0.5 to 1.5, were attributed to the temperature differences. Indeed, Beyler [1983] observed temperatures below 850 K whereas Gottuk achieved temperatures above 920 K (postflashover conditions). From chemical kinetics, the chemical reaction oxidizing CO to CO₂ changes from a very slow reaction to a fast reaction between 800 K and 900 K.

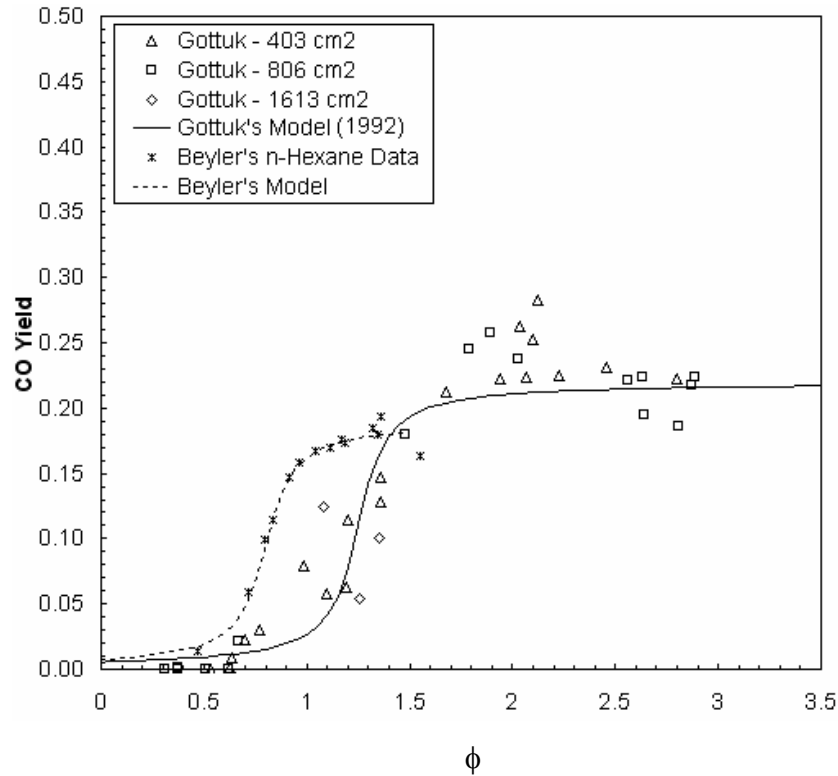


Figure 1-4: Unnormalized carbon monoxide yields as a function of the global equivalence ratio based on the work by Gottuk [1992] compared with *n*-hexane data from Beyler [1983]. (Taken from Wieczorek [2003])

In addition to the conclusions made previously based on hood experiments, the following conclusions were made by Gottuk et al. [2002] on compartment fire in an ideal two-layer system:

- Within the upper layer, the spatial variation of both the temperature and composition is minimal.
- The temperature of the combustion gases greatly affects the levels of CO produced.
 - At temperatures below 850 K, no or very little oxidation of CO into CO₂ occurs.
 - As the temperature increase above 850 K, the reaction that converts CO to CO₂ occurs faster.

1.3.2.2 Compartment with Prototypical Building Features

The dynamic of actual building fires is more complicated than the one simulated previously by bench-scale experiments. More realistic scenarios, such as fires enclosed in compartments with a single vent, have been investigated to replicate the flow dynamic occurring in a room with a single doorway, Figure 1-5.

Extending the bench-scale equivalence ratio methodology to the data obtained on full-scale apparatus required the global equivalence ratio to be assumed equal to the plume equivalence ratio.

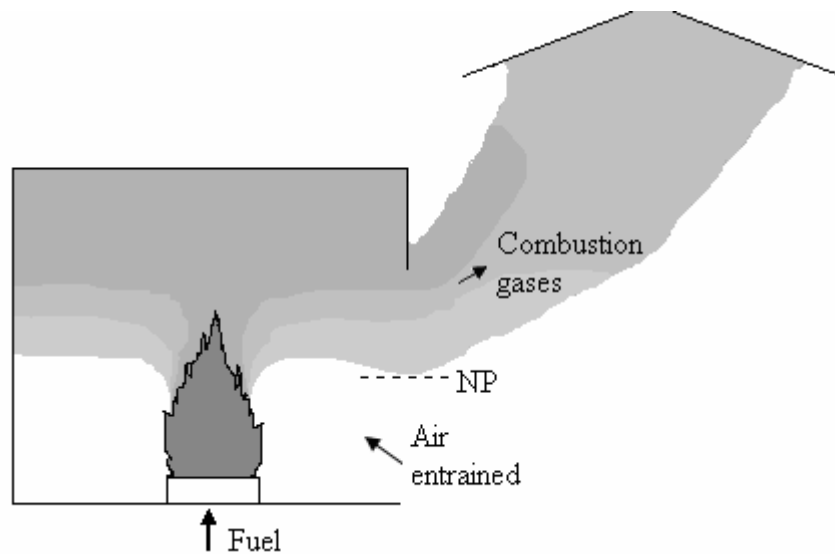


Figure 1-5: Schematic of a compartment with prototypical building features.

Bryner et al. [1994] performed tests in a 2/5-scale ISO 9705 standard compartment (0.98 m by 1.46 m by 0.98 m high). As opposed to the ideal two-layer system, the air and the combustion gas were allowed through the same vent referred to as a doorway (0.81 m high and 0.48 m wide). The hot expanding layer of combustion gas contiguous to the ambient air directly outside the compartment established a pressure gradient across the doorway. The combustion gas was flowing out through the upper region of the doorway entraining the air through the lower region toward the burner. After comparing measurements at various locations within the compartment, Bryner [1994] reported that significant spatial variations, both in temperature and gas composition, existed within the upper layer. In this scenario, the upper layer could not be

considered homogeneous and a single point measurement was not sufficient anymore to represent the flow.

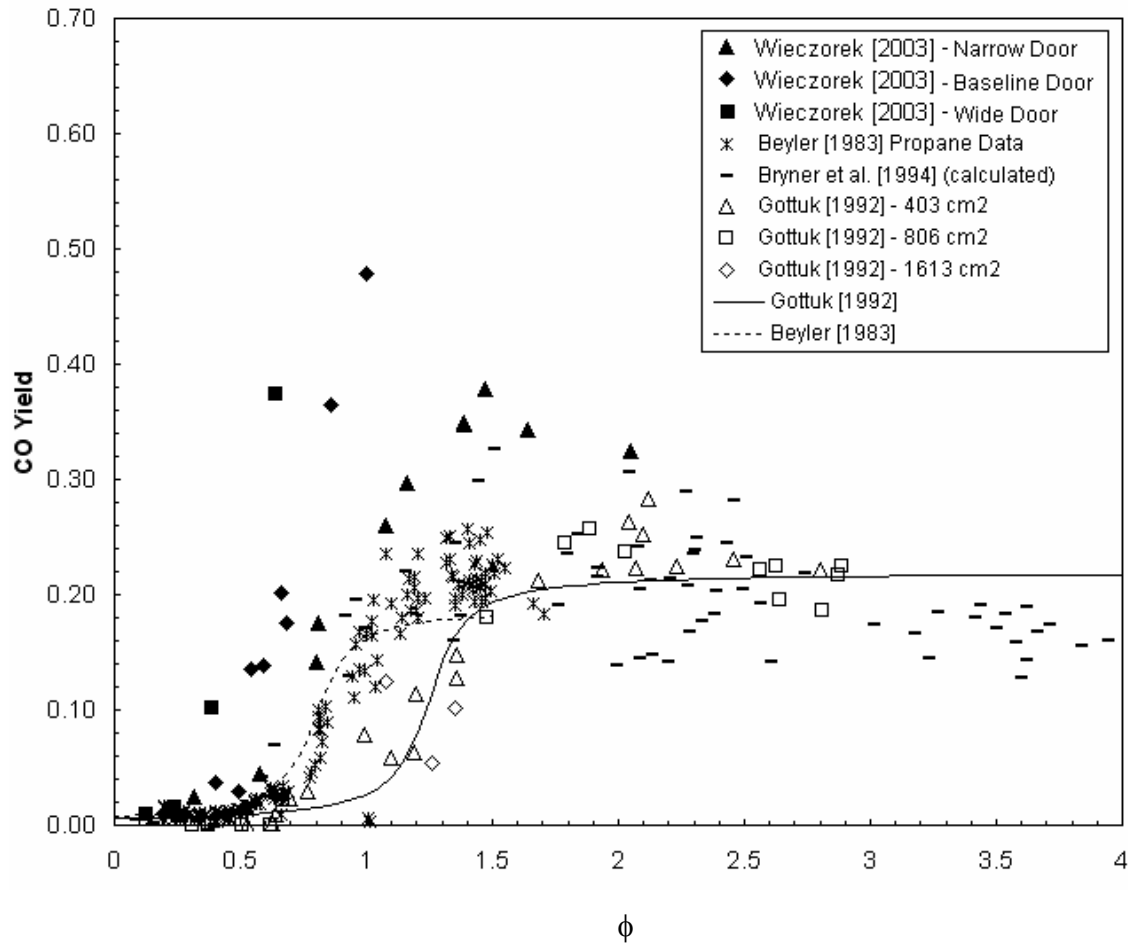


Figure 1-6: Carbon monoxide yields as a function of the equivalence ratio and doorway width based on the work of Wieczorek [2003] compared with data from Gottuk [1992], Beyler [1983], and Bryner *et al.* [1994] in addition to correlations from Gottuk [1992] and Beyler [1983]. (Taken from Wieczorek [2003])

Recent investigations by Wieczorek [2003] were conducted at Virginia Tech on gaseous propane fires in half-scale ISO 9705 compartment (1.2 m by 1.8 m by 1.2 m high). Three doorway sizes were studied for ideal heat release rates ranging from 50 kW to 500 kW. The doorways were 0.82 m high by 0.16 m, 0.33 m and 0.66 m wide (Termed “narrow”, “baseline” and “wide” door respectively). During a steady state period, detailed mappings of the major species local mole fractions, local gas velocity and local

temperature were obtained at the doorway cross-section. The air entrainment mass flow rate was then calculated using an integration scheme and combined with the measured fuel mass flow rate to obtain the global equivalence ratio. For most of the heat release rates studied, external burning was observed and the species yields were calculated based on the fuel burning inside the compartment. The carbon monoxide yields as a function of the global equivalence ratio and doorway width from the work of Wieczorek [2003] are presented in Figure 1-6 along with the work of Beyler [1983], Bryner [1994] and Gottuk [1992].

Wieczorek [2003] reported three different curves, one for each doorway, and concluded that the methodology failed to correlate the data for this scenario. Consistently higher carbon monoxide yields were also observed for the single vent configuration when compared to the hood experiments and the ideal two-layer compartment experiments at equal equivalence ratio. Wieczorek [2003] made the following conclusions:

- The assumption that the global equivalence ratio was equal to the plume equivalence ratio cannot be made for this configuration for the following reasons:
 - The upper-layer was not well-mixed
 - Not all the air entrained inside the compartment was entrained into the fire plume; unconsumed oxygen was present inside the combustion gas flowing out of the compartment.
- Carbon monoxide levels were significantly higher than the one obtained from hood experiments and Ideal two-layer compartment experiments for equal ideal heat release rates. This discrepancy indicated a different reactor configuration; the air was not entrained into the fire plume from all around the burner.
- The global equivalence ratio fails to correlate the species data for the different ventilation conditions.

- The global equivalence ratio parameter does not account for the presence of external burning at the doorway.

Based on the limitations of the equivalence ratio, an alternative methodology was developed by Wieczorek [2003]. The new proposed parameter was a non dimensional heat release rate. Equation 1-2 defined the new parameter as the ratio of the ideal heat release rate, $\dot{Q}_{ideal}$, divided by the heat release rate required for the flame to reach the top of the doorway, $\dot{Q}_{Flame\ Extensions}$.

$$\tilde{Q} = \frac{\dot{Q}_{ideal}}{\dot{Q}_{Flame\ Extensions}} \quad (1-2)$$

As opposed to the global equivalence ratio, the non-dimensional heat release is based on geometrical parameters of the compartment since the doorway geometry affects the $\dot{Q}_{Flame\ Extensions}$.

Because of the limited knowledge on flame extension predictions, the heat release rate $\dot{Q}_{Flame\ Extensions}$ was estimated by direct observation of the experiments. External burning occurred for all heat release rates investigated, with the exception of five, allowing the determination of $\dot{Q}_{Flame\ Extensions}$ for the three doorways, Table 1-2.

Table 1-2: $\dot{Q}_{Flame\ Extensions}$ for the three doorways

Doorway Geometry	$\dot{Q}_{Flame\ Extensions}$ (kW)
Narrow	91
Baseline	127
Wide	107 – 203 (155)

The carbon monoxide yields, based on the burning inside the compartment, are presented as a function of the non dimensional heat release rate in Figure 1-7. Wieczorek [2003] reported that applying this methodology to the data indicated a good correlation for all four species.

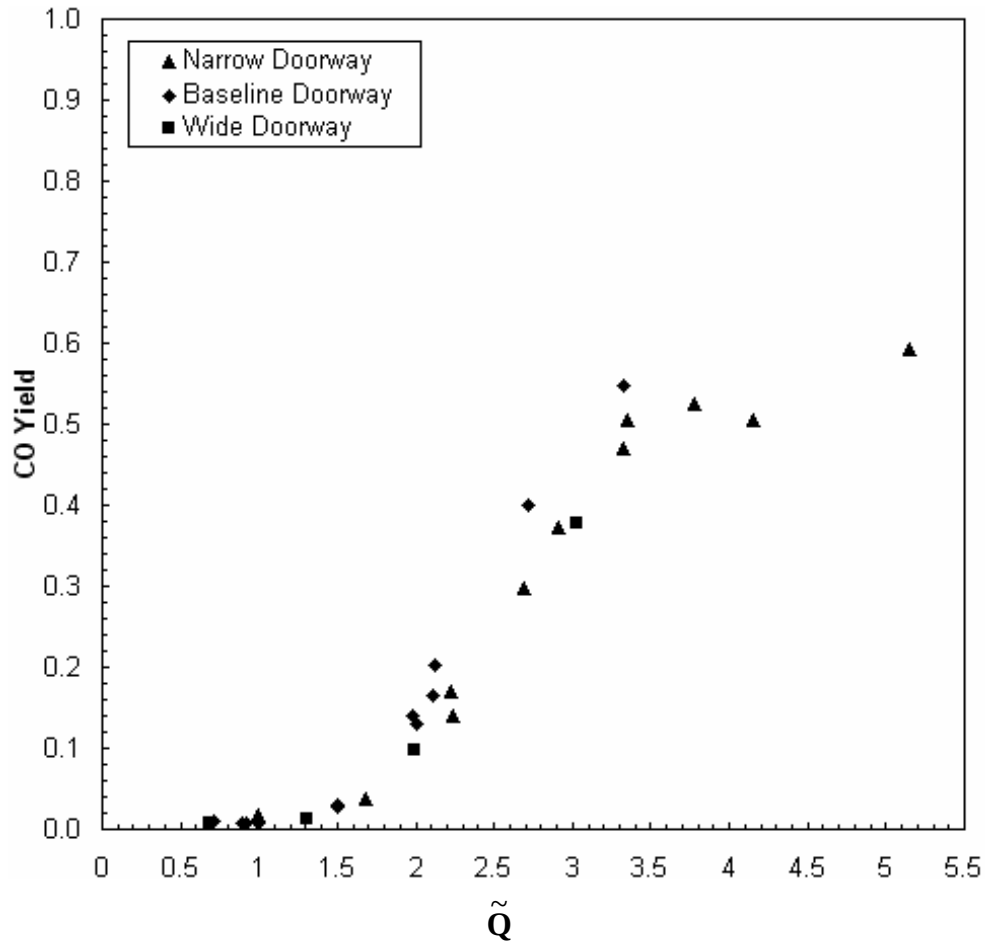


Figure 1-7: Carbon monoxide yield (based on combustion within the compartment) as a function of the non dimensional heat release rate. (Taken from Wieczorek [2003])

Prior to the presence of external burning ($\tilde{Q} < 1$), the levels of carbon monoxide were constant and low (below $0.01 \text{ g}_{\text{co}}/\text{g}_{\text{fuel}}$). For values of $\tilde{Q} > 3.5$, the CO Yield reached a plateau approaching a value of $0.5 \text{ g}_{\text{co}}/\text{g}_{\text{fuel}}$. A large increase can be observed for values of $\tilde{Q}$ ranging between 1.25 and 3.5.

A correlation based on a regression analysis was developed for the carbon monoxide yields shown in Figure 1-8. Similar correlations were obtained for the other species. Wieczorek [2003] determined that the data for the CO yield, over the range of $\tilde{Q}$ investigated, were best represented as a Sigmoidal or "S-shaped" growth curve.

Equation (1-3), gives the yield of carbon monoxide based on the fuel burnt inside the compartment as a function of the non-dimensional heat release rate.

$$Y^{\text{CO}} = \frac{a \cdot b + c \cdot \tilde{Q}^d}{b + \tilde{Q}^d} \quad (1-3)$$

With:

$$a = 0.0062$$

$$b = 219.4$$

$$c = 0.58$$

$$d = 5.77$$

Reported standard error = 0.030

R^2 value = 0.99

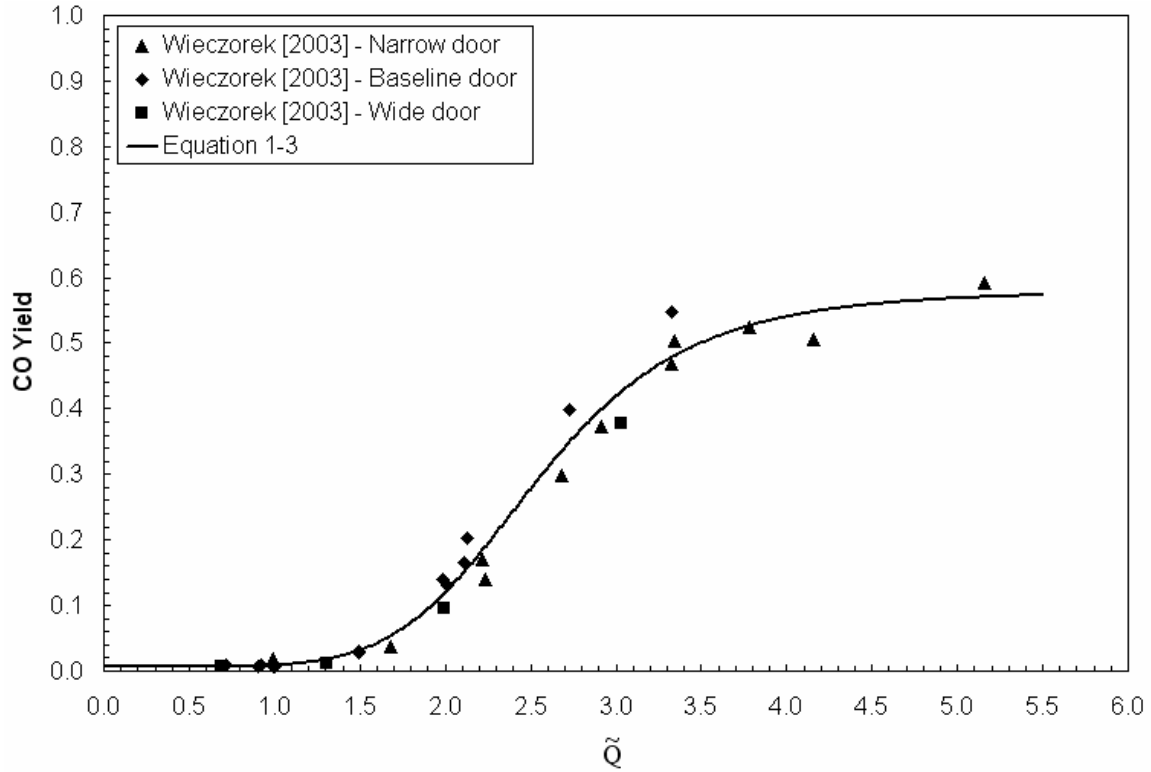


Figure 1-8: Carbon Monoxide yields (based on combustion within the compartment) as a function of $\tilde{Q}$ along with a curve fit to the data.

This correlation was based on the data obtained and was meant to be used over the range it was developed for.

1.4 TRANSPORT OF SPECIES TO ADJACENT SPACES

When studying the transport of species produced by an enclosure fire, the conditions in the adjacent space are of most importance. The species yields at the compartment exit plane should not be viewed as the final species yields being transported. Indeed, reactions can occur in the zone directly outside the vent depending on the temperature, the oxygen availability and the geometry of the adjacent space.

1.4.1 Transport to Unconfined Adjacent Spaces

An adjacent space is considered unconfined if there is no ceiling or side walls to obstruct or redirect the flow of exhaust gas and/or external burning. The gases directly outside the vent are buoyancy driven. Gottuk [1992], in his study on the ideal two-layer compartment, reported in Section 1.3.2.1, also compared the measurement made within the compartment to a measurement made inside the collection hood. For $\phi < 1.5$, measurements at both locations were in agreement on the species level. At higher ϕ , where external burning was observed, the carbon monoxide level measured inside the collection hood were considerably lower than the one measured within the compartment. Gottuk [1992], attributed the decrease of carbon monoxide level to the oxidation of carbon monoxide into carbon dioxide due the high temperature ($T > 850 \text{ K}$) provided by the external burning and the oxygen availability in the unconfined adjacent space.

More recently, Lönnermark et al. [1997] used a full scale ISO 9705 compartment to compare carbon monoxide levels between the compartment doorway and the exhaust hood using solid and liquid fuel sources. Agreeing with the observation made by Gottuk [1992], for $\phi > 1.5$ where external burning occurred, carbon monoxide levels were lower inside the exhaust hood than at the compartment doorway.

1.4.2 Transport to Confined Adjacent Spaces; Hallway Studies

Confined adjacent spaces such as hallways, change the dynamic of the flow outside the compartment. Instead of a buoyancy driven flow, a ceiling jet is formed. The air entrainment also is limited and heat is lost by conduction to the boundaries (walls and ceiling).

Ewens [1994] examined the oxidation of fire exhaust gases during their transport along a hallway. Experiments were performed in the ideal two layer compartment used by Gottuk [1992] with a 3.66 m long hallway in a head-on configuration, Figure 1-9. The effects of the fluid dynamic within the hallway were investigated by varying the inlet and exit hallway soffit sizes. The oxidation of the fire exhaust gases was determined to be a function of:

- The fluid dynamics along the hallway.
- The oxygen level in the exhaust gases entering the hallway.
- The exhaust gas temperature inside the hallway.
- The fuel vaporization rate (n-hexane) within the compartment.

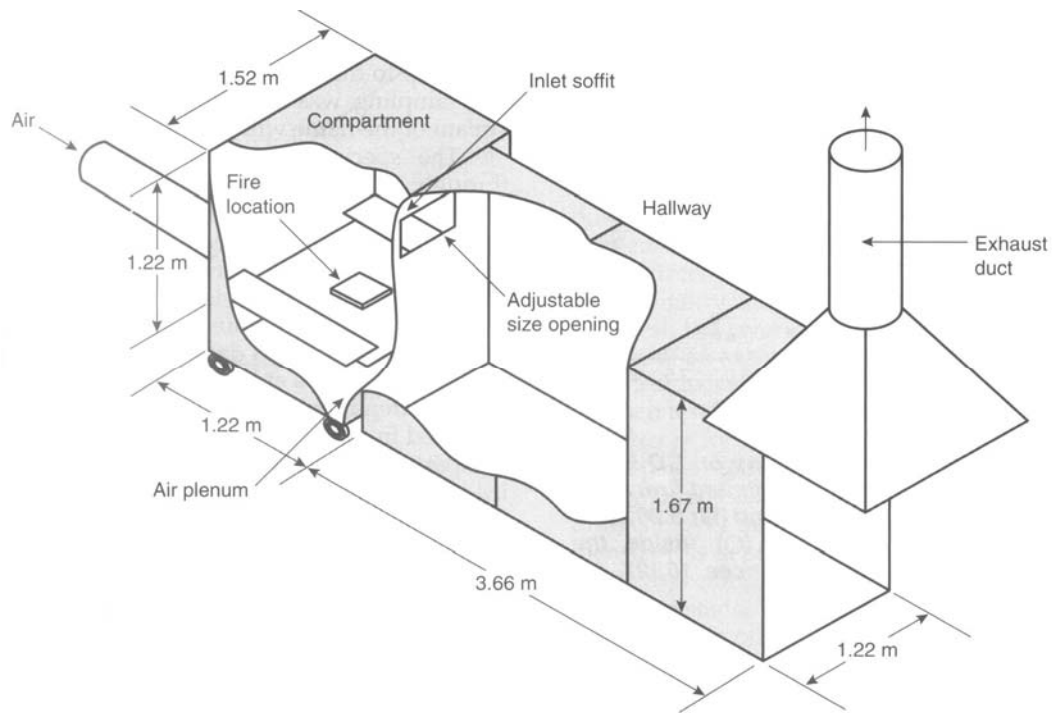


Figure 1-9: Ideal two-layer compartment / Hallway in head on configuration for species transport study conducted by Ewens [1994]. (Image taken from Gottuk and Lattimer [2002])

Lattimer [1996] (in a follow up work of Ewens [1994]), performed similar experiments with the hallway connected in a side-on configuration, Figure 1-10. Lattimer [1996] reached the same conclusions as Ewens [1994] but observed a different flow dynamic. The exhaust gases through the window were allowed to expand as ceiling jets along the ceiling until they reached the opposite wall of the hallway. Corner vortices were observed and Lattimer [1996] reported a non-uniform spatial distribution of the carbon monoxide levels in the adjacent space.

The tragedy that occurred at Hillhaven Nursing Home is an example of non-uniformity in the spatial distribution of the carbon monoxide levels. Most of the victims were found in rooms located across the hallway from the room where the fire originated. In addition to the draft caused by a wind from the south, geometric parameters such as the width of the hallway or the soffit depth must have played a role in the transport of the carbon monoxide to these particular rooms.

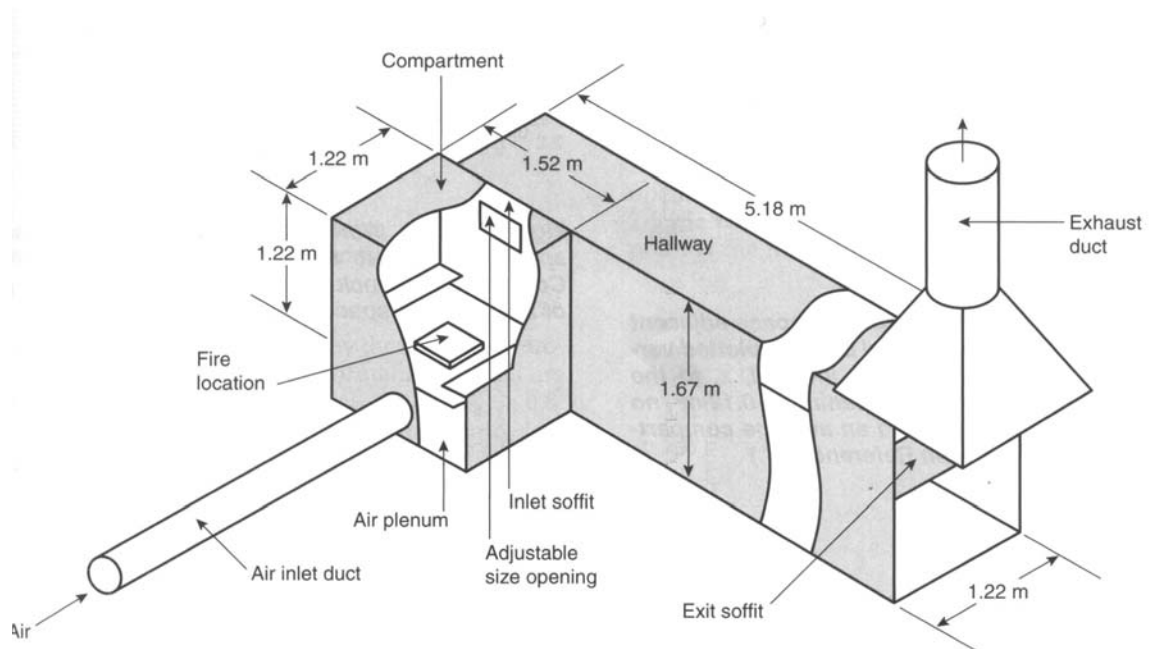


Figure 1-10: Ideal two-layer compartment / Hallway in side-on configuration for species transport study conducted by Lattimer [1996]. (Image taken from Gottuk and Lattimer [2002])

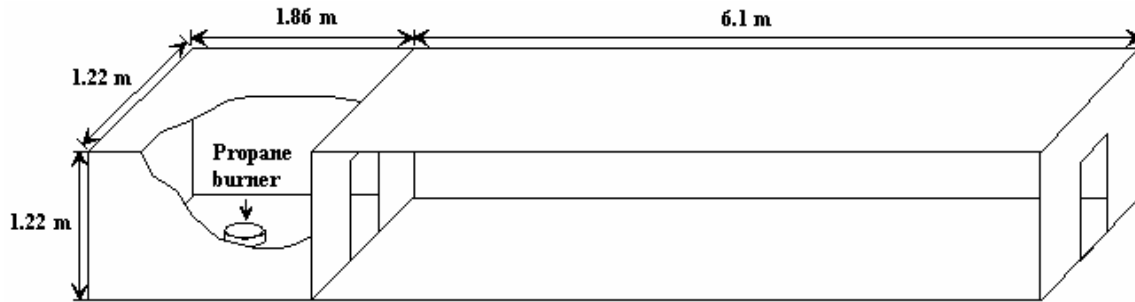


Figure 1-11: Half-scale ISO 9705 Compartment / Hallway in head-on configuration for species transport study conducted by Wieczorek [2003]. (Image taken from Wieczorek [2003])

Wieczorek [2003] conducted a transport study with a hallway connected to the half-scale ISO 9705 compartment in a head-on configuration; Figure 1-11. The objective of that study was to determine the effects of the ventilation size located at the exit of the 6.1m long hallway on the air entrainment rates and the species transport. The baseline doorway (0.82 m high by 0.33 m wide) was installed at the compartment exit. Three ventilation sizes were investigated at the hallway exit, namely the narrow, baseline and wide doorways. For each configuration, three heat release rates were studied insuring that no or little external burning was occurring.

For a fixed ideal heat release rates, Wiecezorek [2003] observed a decrease in the air entrainment into the compartment when the hallway exit doorway width was reduced. However, the air entrainment into the compartment and into the hallway did not show a dependency to the ideal heat release rate when the hallway exit doorway width was kept constant.

Although, the air flow rate into the compartment was affected by the addition of the hallway and the hallway exit doorway, no noticeable impact on the species generation within the compartment was observed for over ventilated fires.

The addition of the hallway exit doorway forced the combustion gases to accumulate along the ceiling of the hallway. For $\tilde{Q} < 1.0$, mixing of the combustion gases

was reported by Wieczorek [2003] due to the smoke buildup. The composition of the exhaust gases flowing out of the hallway exit was homogeneous as opposed to stratified at the compartment doorway.

Only a few experiments with little external burning ($\tilde{Q} > 1.0$) allowed Wieczorek [2003] to observe the reduction in carbon monoxide levels attributed to oxidation reactions between the compartment exit and the hallway exit.

1.5 OBJECTIVES OF THE PRESENT RESEARCH

The primary goal of this research is to improve the general knowledge of the combustion process occurring in structural fires. Understanding the parameters influencing the carbon monoxide generation and transport from an enclosure fire would provide useful data for designing safer buildings. In order to apply experimentally developed theory to actual buildings, it is important to relate those species levels to physical parameters such as the room and the vent dimensions, the walls and the ceiling thermophysical properties, the fuel type and its mass loss rate. This methodology allows the calculation of non-dimensional parameters such as the equivalence ratio ϕ , or the non-dimensional heat release rate $\tilde{Q}$.

The objectives for the present research were set as:

- Analyze the effects of geometrical parameters on the fire dynamic and the combustion process occurring in a compartment fire with prototypical building features and a hallway connected to it.
- Determine the parameters controlling the oxidation and the transport of species generated in a compartment fire with prototypical building features to adjacent spaces
- Develop a methodology capable of predicting the toxic species levels generated in a building fire and their transport to remote locations.

CHAPTER 2 - EXPERIMENTAL APPARATUS AND PROCEDURES

A complete description of the test apparatus, test procedure and data reduction calculation used for this study is given in this chapter.

2.1 EXPERIMENTAL APPARATUS

2.1.1 Experimental Facilities

2.1.1.1 Scaled Test Compartment and Hallway

The experiments were conducted in the same test apparatus as the one used by Wieczorek [2003] in his research. The compartment was built to the dimensions of a half-scale ISO 9705 standard compartment, Figure 2-1. The interior compartment dimensions were 1.17 m wide by 1.78 m deep by 1.17 m high. The exterior of the compartment was made out of a thin sheet of steel and the inside was lined with 25.4 mm (1 inch) thick Thermal Ceramics M-board. To insure a proper scaling of the gas velocities and residence times within the compartment, the doorway dimension used for this study was scaled based on dynamic flow similarity (ventilation and residence time parameters). [McKay 2002] This doorway was named “baseline” and its width was 0.33 m with a height of 0.82 m. This corresponded to an opening area of 0.27 m^2 .

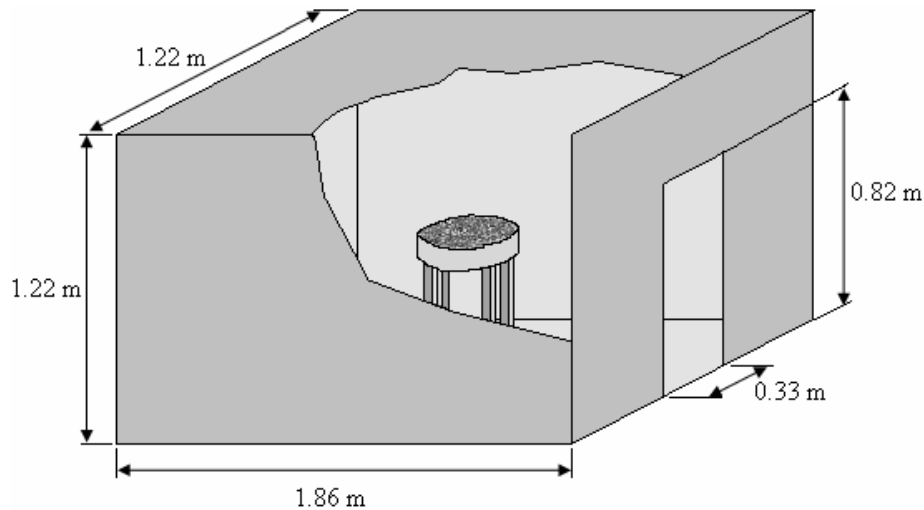


Figure 2-1: Half-Scaled ISO 9705 Compartment, with variable height fire source.

The test compartment was linked to a hallway which was made out of a steel frame, Figure 2-2. The walls and ceiling attached to the frame were made out of one layer of fiberboard (Thermal Ceramics M-board) and a layer of drywall on the outside. The concrete floor was also covered with fiberboard. The hallway was 6.1 m long and its cross sectional area was that of the compartment. The interior dimensions were 1.17 m wide and 1.17 m high.

The end of the hallway was designed in order to study different ventilation conditions. These various ventilation conditions were obtained by changing the size of the doorway installed at this location. The doorway height remained fixed and equal to the one used for the compartment doorway (0.82m).

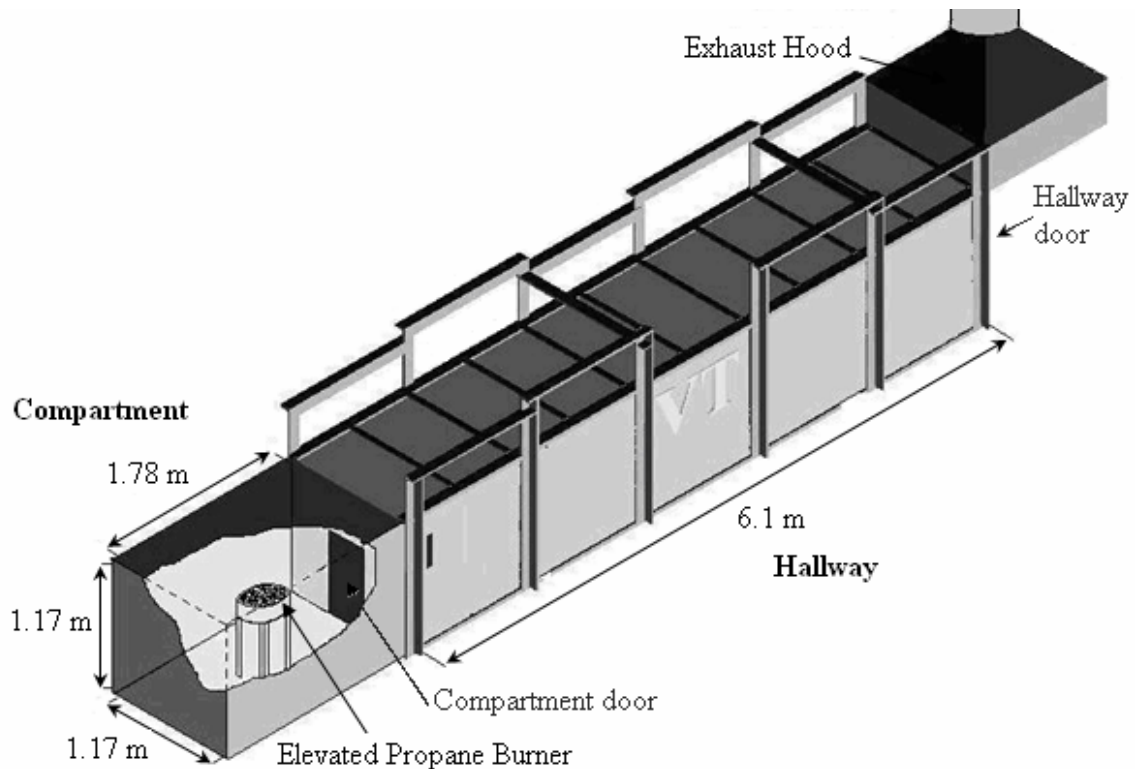


Figure 2-2: Half-scaled ISO 9705 Compartment with hallway in a head-on configuration.

2.1.1.2 Concrete Enclosure

In order to eliminate cross wind effects that would induce forced ventilation, the end of the hallway was located in a concrete enclosure Figure 2-3 (a). This enclosure was 3.1 m wide by 3.05 m deep, by 2.84 m high. The top of the enclosure was partially covered by a steel ceiling, while the front 0.81 m was open. The schematic of the top view and the east view is shown in Figure 2-3 (b).

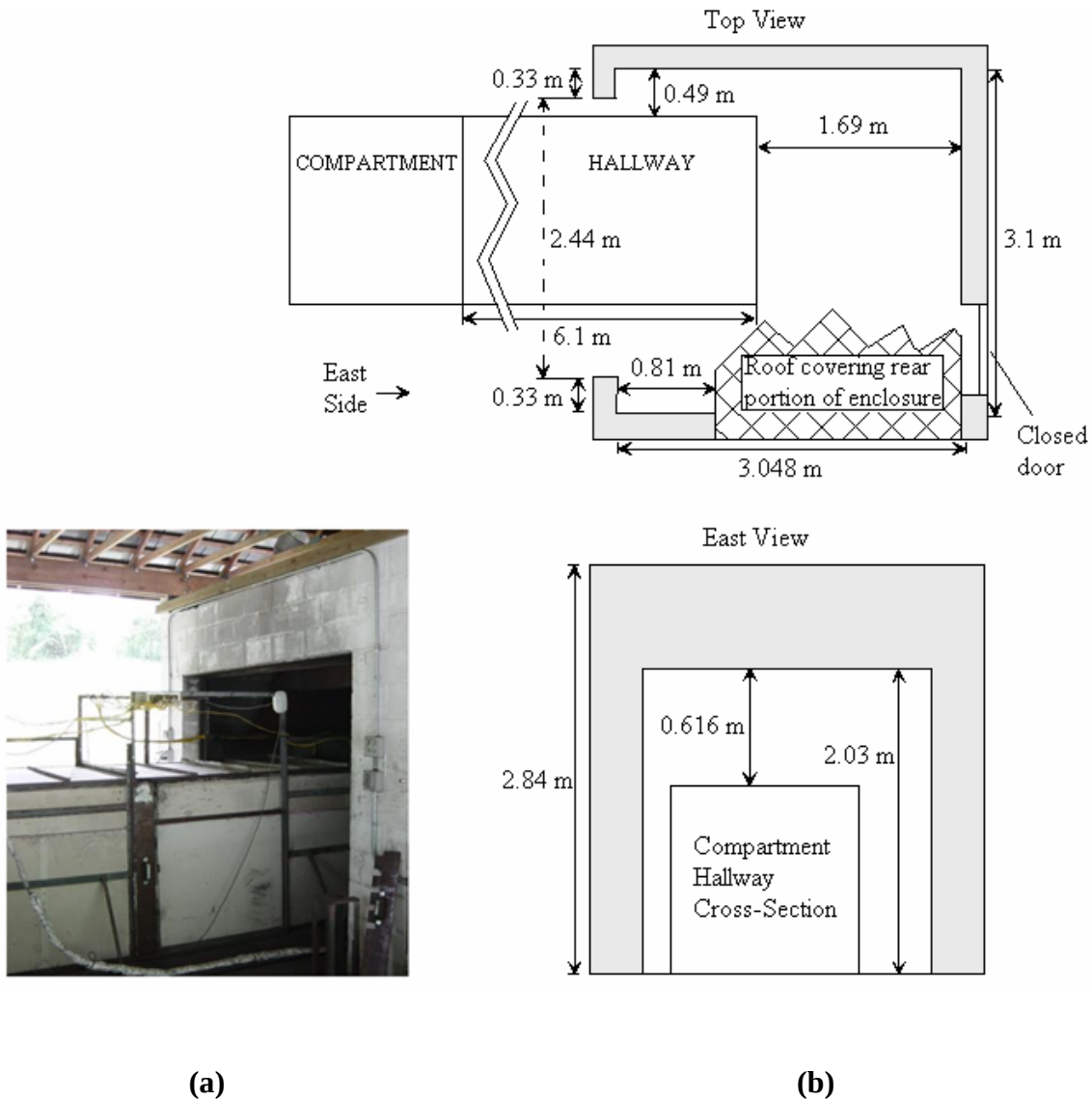


Figure 2-3: (a) Picture of the enclosure, (b) Top view and east view of concrete enclosure. (Image adopted from Wieczorek [2003] and modified)

2.1.1.3 Exhaust Hood

For safety measures, a 1.5 m by 1.5 m exhaust hood was located over the hallway doorway to collect exiting combustion gases. A 5000 cfm blower was connected to the hood via a 0.46 m diameter duct, Figure 2-4. The exhaust rate could be regulated by adjusting the louvers located prior to the blower. Although 5 possible settings were available (0%, 25%, 50%, 75% and 100% of the maximum flow rate), all the tests presented in this study were performed at the maximum flow rate.

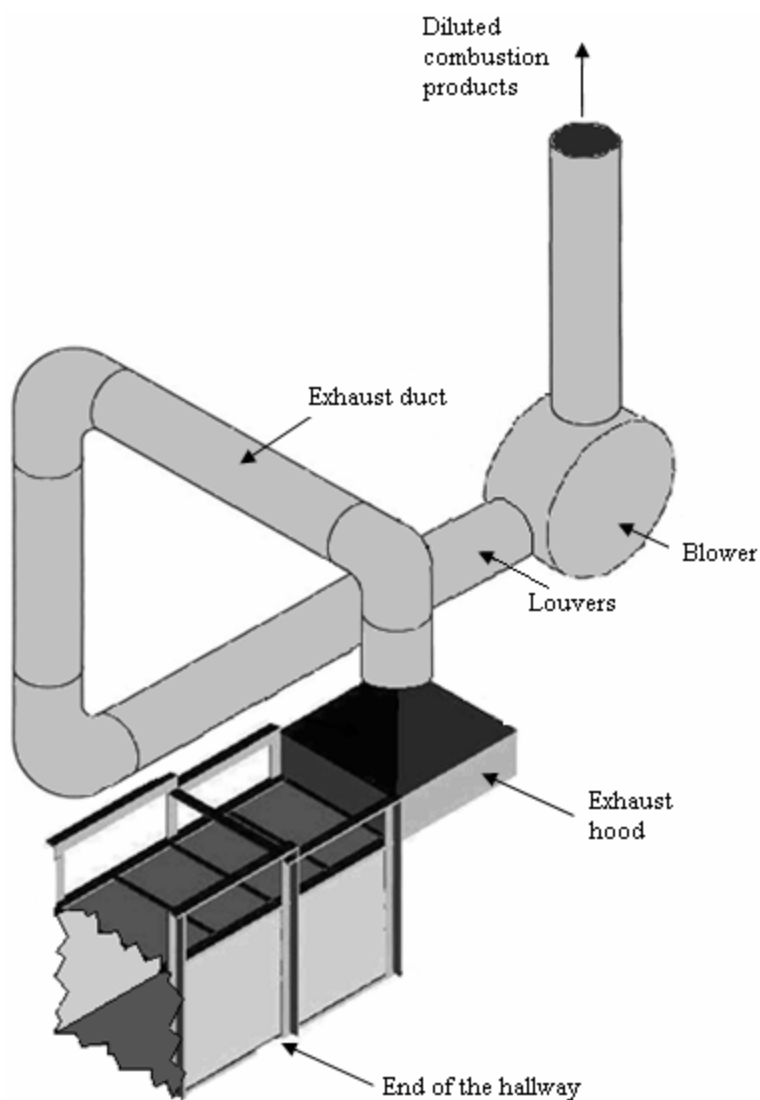


Figure 2-4: Exhaust system.

2.1.2 Continuous Fuel Line and Elevated Burner

Repeatability of long duration tests and an accurate monitoring of the fuel mass loss rate are necessary for this type of research. These requirements could be satisfied by using a gaseous fuel such as propane, a mass flow meter and an appropriate burner. To simulate buoyancy driven diffusion flames as opposed to momentum driven, the burner had to provide a large pressure drop between the gas inlet port and the top of the burner where the base of the flame was located. This was accomplished by constructing the burner shown in Figure 2-5 (a). The gas, regulated at a pressure of 10 psig, was introduced into a two-inch plenum through the bottom of the burner via a one-inch diameter pipe. The gas then flowed through three layers to insure the proper pressure drop. The first layer was a perforated plate, followed by the second layer of fine wire mesh. These two layers were covered with a 1.5-inch layer of fine marble chips to create the third layer. The burner was 0.305 m in diameter corresponding to an area of 0.073 m² and 0.102 m high. Although able to provide heat release rates up to 1.2 MW, this study was limited to 100 kW heat release rates to keep the fire contained within the compartment.

To conduct the parametric study of the burner elevation, an adjustable burner stand had to be built. It was made out of steel and offered the possibility to be adjusted to five different heights ($h/H_{\text{Door}}=0.5$, $h/H_{\text{Door}}=0.625$, $h/H_{\text{Door}}=0.75$, $h/H_{\text{Door}}=0.875$, $h/H_{\text{Door}}=1$) with h corresponding to the elevation of the top of the burner and H_{Door} to the doorway height (0.82 m). A drawing of the stand with the burner resting on top is shown in Figure 2-5 (b).

Three elevations were investigated in this study. The first one did not require the stand since the burner was resting on the floor ($h/H_{\text{Door}}=0.125$), and the other two corresponded to $h/H_{\text{Door}}=0.5$ and $h/H_{\text{Door}}=0.75$.

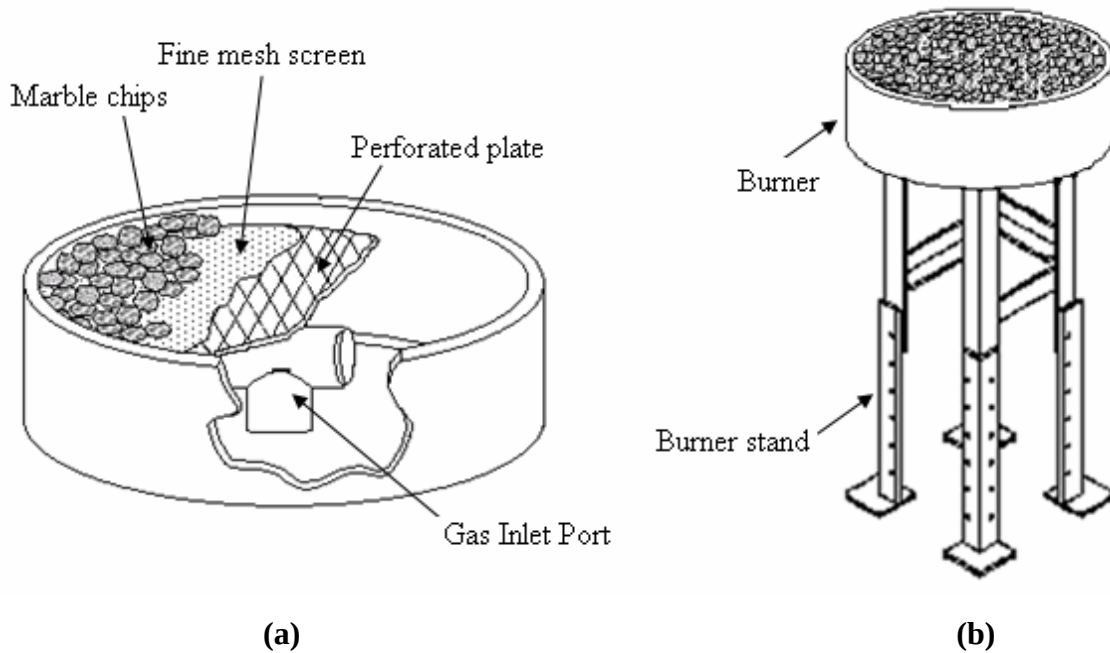


Figure 2-5: (a) Schematic of burner, (b) Burner on the adjustable stand.

Experiments conducted required flow rates of propane in the range of 15 slpm to 80 slpm corresponding respectively to heat release rates between 20 kW and 120 kW. The various heat release rates investigated for this study were obtained by keeping a constant burner diameter and varying the fuel mass flow rate. A fuel supply system consisting of a 500-gal LPG tank, a set of globe valves, a mass flow meter and a needle valve was built for that purpose. The schematic of the continuous fuel supply system is shown in Figure 2-6.

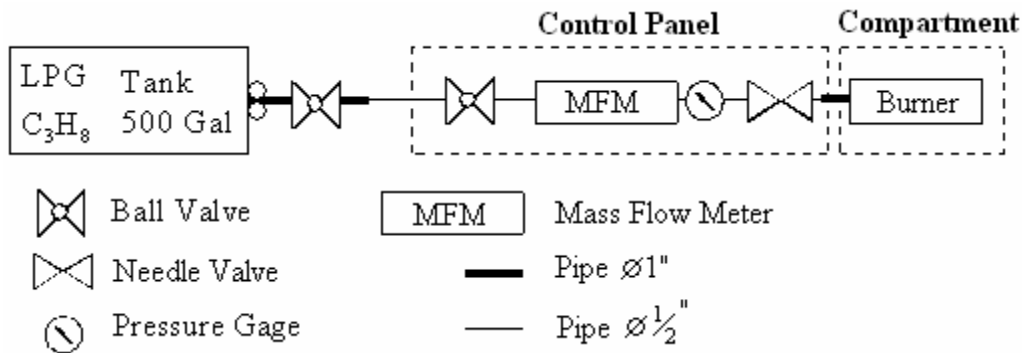


Figure 2-6: Schematic of the continuous gaseous fuel supply system.

The fuel line pressure gage was regulated to 10 psig at the exit of the tank. A one-inch diameter pipe reduced to a half-inch diameter pipe supplied fuel to the mass flow meter. A needle valve was used to vary the fuel mass flow rate at the exit of the mass flow meter. The diameter of the pipe was then increased to one-inch diameter to supply the burner with the desired mass flow rate. The burner provided the appropriate pressure drop to lower the fuel pressure close to one atmosphere. A picture of the control panel is shown in Figure 2-7 (a), as well as a close-up of the Omega Inc. mass flow meter, model FMA 1611 Figure 2-7 (b).



(a)



(b)

Figure 2-7: (a) Picture of the fuel line, (b) Mass flow meter.

2.1.3 Data Acquisition

2.1.3.1 Local Measurements

The data to be acquired during each experiment included local temperature measurements, local velocity measurements and local gas composition measurements at specific locations.

2.1.3.2 Temperature Measurements

Temperature measurements were obtained using aspirated type K thermocouples. They were mounted on rakes based on the recommended suction velocities of Blevin et al. [1999]. Each rake consisted of a maximum of 5 thermocouples in order to limit the size of the pumps.

The pump size and rake tubing dimensions were based on a minimum suction velocity of 20 m/s for each probe inlet. The pumps were Gast model #2567 and had an open flow rate of 21.0 cfm at a maximum pressure of 15 psig. The main body of the rake was built with $\frac{3}{8}$ -inch stainless steel pipes. The housing of each thermocouple was made out of $\frac{1}{4}$ -inch stainless steel tubing.

Twenty two aspirated thermocouples were used for each test. Nine thermocouples, located in the front right corner of the compartment and evenly spaced along the wall, measured the vertical temperature distribution. They were mounted on two rakes as shown in Figure 2-8 (a). The top rake consisted of five thermocouples and the bottom one of four.

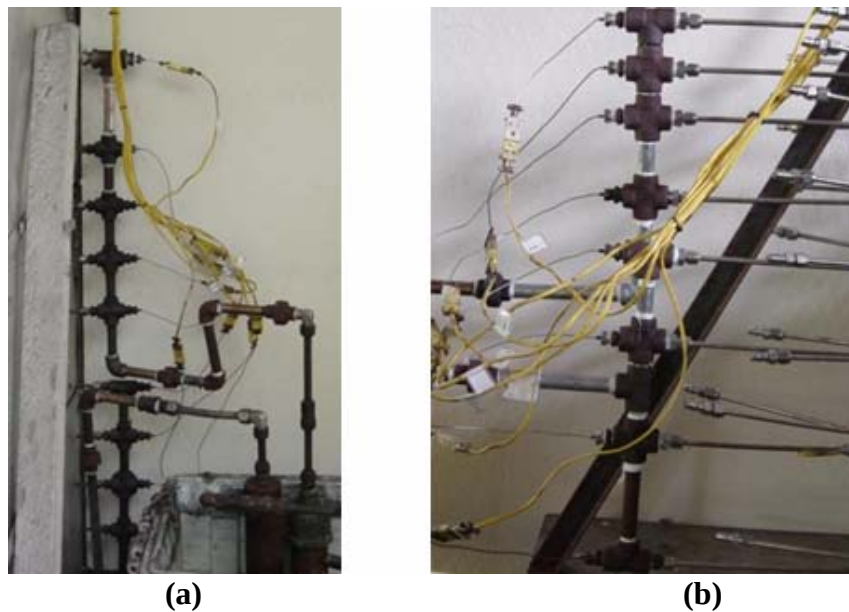


Figure 2-8: (a) Compartment thermocouple rake, (b) Thermocouple rake on the compartment sampling rake.

The remaining thirteen thermocouples were installed on the two rakes of sampling probes used to map each cross-section investigated (i.e.: Eight at the compartment doorway and five at the hallway-exit doorway). A picture of the two thermocouple rakes (four thermocouples each) installed on the compartment doorway sampling rake is shown

in Figure 2-8 (b). Each sampling probe mounted on the sampling rakes incorporates a thermocouple for the measurement of the local temperature at the point of sampling.

Three bare-bead thermocouples were installed along the ceiling of the hallway. Two additional thermocouples read the ambient temperature and the exhaust gas temperature inside the hood.

Temperatures were measured continuously and recorded every second throughout the duration of the test.

The three sets of coefficients in Table 2-1 were used to convert the voltage readings to temperature values depending on the temperature range. The conversion formula for Type K thermocouples is,

$$T = a_0 + \sum_{i=1}^n a_i \times \text{Volt} \quad (2-1)$$

Where:

T is the Temperature in Degree Celsius.

Volt is the voltage reading from the thermocouple in millivolts.

$a_0 \dots a_9$ are the polynomial coefficients depending on the temperature.

Table 2-1: Conversion coefficients from voltage reading to temperature for type K thermocouples

Coefficients	Temperature Ranges		
	-200C to 0C	0C to 500C	500C to 1372C
a₀	0	0	-1.318058E+2
a₁	2.5173462E-2	2.508355E-2	4.830222E-2
a₂	-1.1662878E-6	7.860106E-8	-1.646031E-6
a₃	-1.0833638E-9	-2.503131E-10	5.464731E-11
a₄	-8.9773540E-13	8.315270E-14	-9.650715E-16
a₅	-3.7342377E-16	-1.228034E-17	8.802193E-21
a₆	-8.6632643E-20	9.804036E-22	-3.110810E-26
a₇	-1.0450598E-23	-4.413030E-26	---
a₈	-5.1920577E-28	1.057734E-30	---
a₉	---	-1.052755E-35	---

2.1.3.3 Fire Gases Velocity Measurement

Bi-directional Pitot probes at each sampling location were used to obtain the local velocity, Figure 2-9 (a). The pressure difference was measured using Setra Inc. model 264 low differential pressure transducers, Figure 2-9 (b). They had an accuracy of 1.0 % full scale. The response time given by the manufacturer was approximately 50 msec.

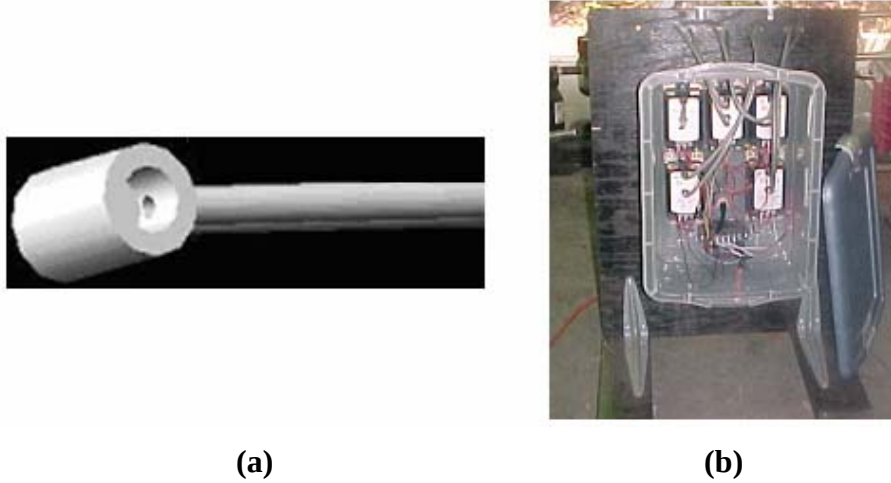


Figure 2-9: (a) Drawing of bi-directional Pitot probe, (b) Pressure transducers.

Two different ranges were used in order to capture higher velocities expected at the top of the doorway (± 0.1 inches and ± 0.25 inches of water column). The output signal was 0 V to 5 V and was linear with respect to the pressure difference, Figure 2-10. Equation (2-2) was used to convert the signal from volts to inches of water column.

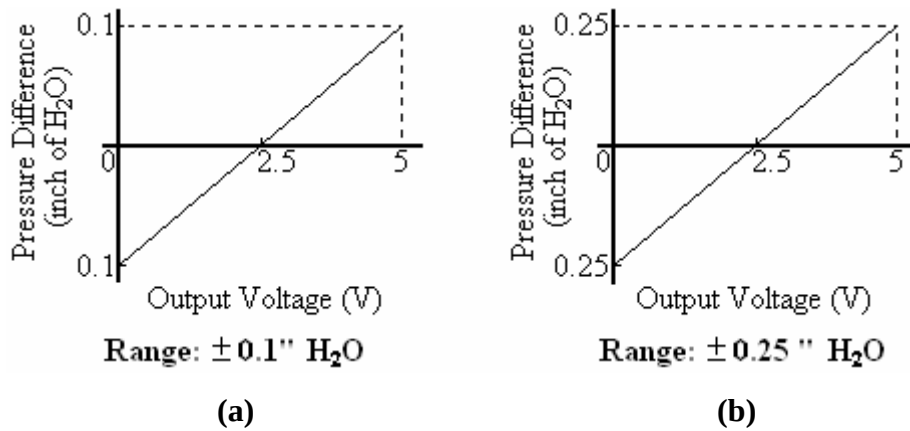


Figure 2-10: Signal conversion for pressure transducers; (a) Range: ± 0.1 " H_2O and (b) Range: ± 0.25 " H_2O .

$$\Delta P = a \times \text{Volt} + b \quad (2-2)$$

Where:

Volt is the output voltage in Volts.

ΔP is the pressure difference in inches of water column.

a and b are coefficients depending on the range used, Table 2-2.

Table 2-2: Conversion coefficients for pressure transducers.

Range	$\pm 0.1'' \text{ H}_2\text{O}$	$\pm 0.25'' \text{ H}_2\text{O}$
a	0.04	0.1
b	-0.1	-0.25

The local gas density was calculated from the measured local temperature. Using the pressure difference and a simple Bernoulli analysis, the local velocities were determined from the Equation (2-3),

$$V = C \sqrt{\frac{2\Delta P}{\rho}} \quad (2-3)$$

Where:

C is the flow coefficient equal to 0.93 as recommended by Emmons [1995].

ΔP is the pressure difference.

ρ is the local gas density.

2.1.3.4 Gas Sampling

Prior to analysis, the sampled gas was filtered. A series of three filters was used for this purpose, Figure 2-11. The first filter was used to remove coarse particulates and was made out of stainless steel wool. The second filter was a Balston Model 30/25 with a 100-25-DH filter element, and the third was a Gelman Sciences Inc. glass fiber filter type A/E (47 mm). The filter assembly was wrapped up in heating tape to avoid water condensation resulting in clogging of the coarse filter.

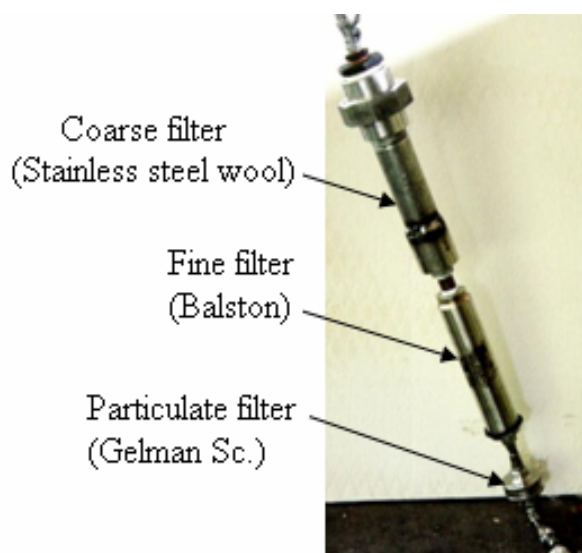


Figure 2-11: Series of filters for sampling line.

After being filtered, the gas traveled in a 7 meter long heated Teflon sampling line, $\frac{1}{4}$ -inch in diameter, and 3 meters of heated stainless steel tubing of same diameter. Another Gelman Sciences Inc. glass fiber filter was used to provide the analyzers with a particulate-free gas. Three analyzers were used to measure the CO, CO₂, O₂ and UHC mole fractions. The non-dispersive infrared CO/CO₂ and paramagnetic O₂ analyzers required a dry gas so the sample line was split. The pump used for this half was a Gast model #47024. Prior to the pump, the gas flowed through a water trap. The water remaining in the gas at the exit of the pump was removed by a Dryite filter. The pump used for the other half, being analyzed by a Flame Ionization Detector (FID) to measure the UHC mole fraction, was a Thomas model # 2107CA18. This sample line remained heated all the way to the FID. A series of valves and bypasses was used to maintain required flow rates and pressures for each analyzer. A schematic of the gas route is shown in Figure 2-12.

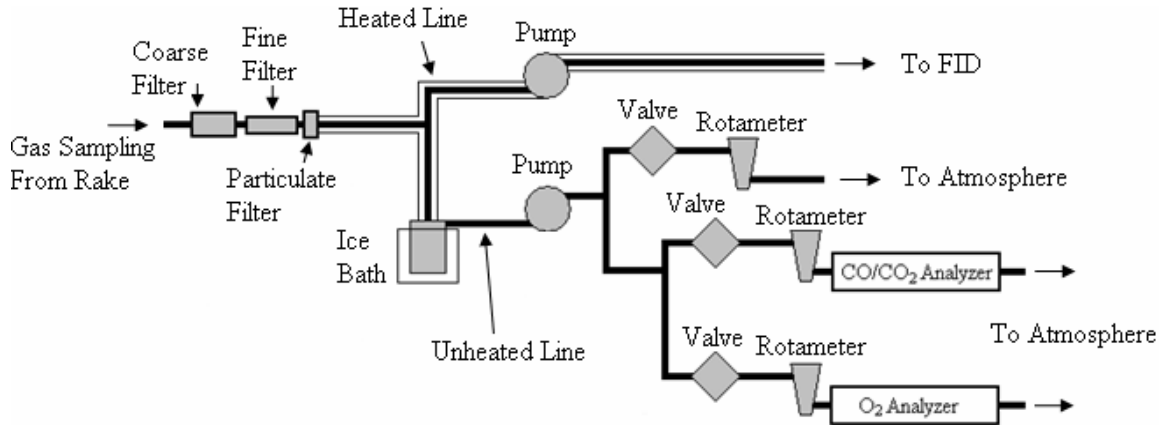


Figure 2-12: Schematic of the gas route from sampling rake to analyzers.

2.1.4 Sampling Rakes

In order to obtain the total mass flow rates and yields of each species through the in-flow and out-flow regions of the doorway cross-sections, the spatial variation of local properties was investigated. The flow properties required at each point were the local species mole fractions, the local velocity and the local temperature. These properties were measured using sampling probes. Each sampling probe consisted of a gas sampling probe, a bi-directional pitot probe and an aspirated thermocouple probe, Figure 2-13.

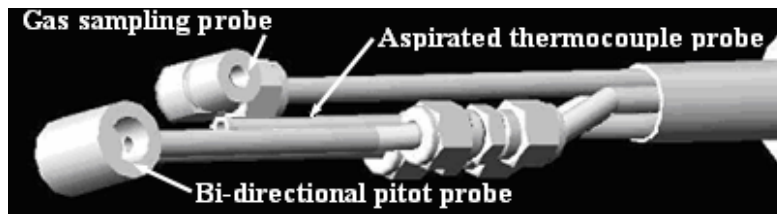


Figure 2-13: CAD drawing of the tip of a sampling probe.

To facilitate and accelerate the mapping process, two rakes of sampling probes, one for each doorway, were used. The spatial variation of flow properties was expected to be greater at the compartment doorway than at the hallway exit doorway. In order to capture these changes, the compartment doorway was equipped with a sampling rake of eight sampling probes, Figure 2-14. Mixing of the combustion gases occurring along the hallway in the smoke layer reduced the spatial variations of gas composition and gas temperature. Only five sampling probes were mounted on the hallway exit rake to investigate the hallway exit doorway, Figure 2-15.



Figure 2-14: Picture of the compartment door sampling rake.

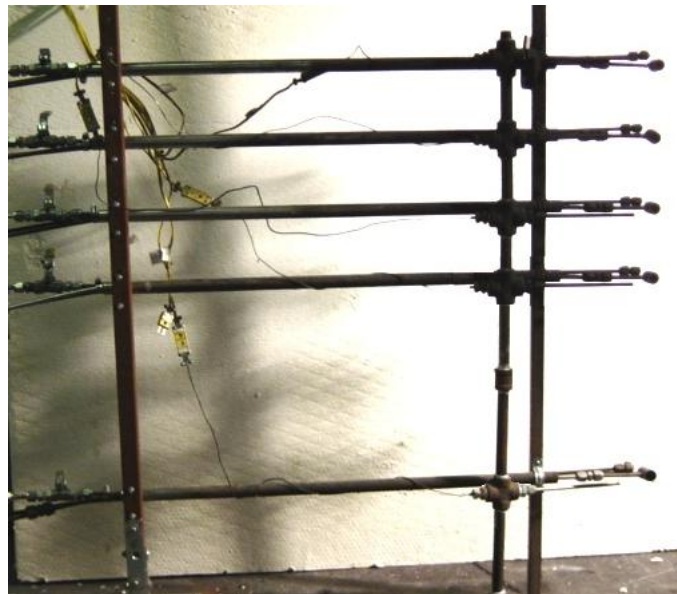


Figure 2-15: Picture of the hallway end door sampling rake.

2.1.5 Gas Analysis

2.1.5.1 CO and CO₂ Gas Analyzer

A Siemens Ultramat 6 dual channel gas analyzer was used to measure CO and CO₂ mole fractions. The two available CO ranges set by the factory were 0 % to 1 % and 0 % to 5 %. Although two ranges, 0 % to 5 % and 0 % to 25 %, were also available for CO₂, only the largest one was used for all experiments.

The gas analyzer was calibrated using Nitrogen gas, to set the zero, and the output signal was linearized internally with respect to the mole fraction using software calibration. The output signal was 4 mA to 20 mA. It was then converted to a 0 V to 5 V signal via a 250 ohm resistor across the output leads. Gas tanks containing different mixtures of CO and CO₂ were used to verify the calibration.

The linearization of the signal with respect to the mole fraction for both CO and CO₂ are shown in Figure 2-16.

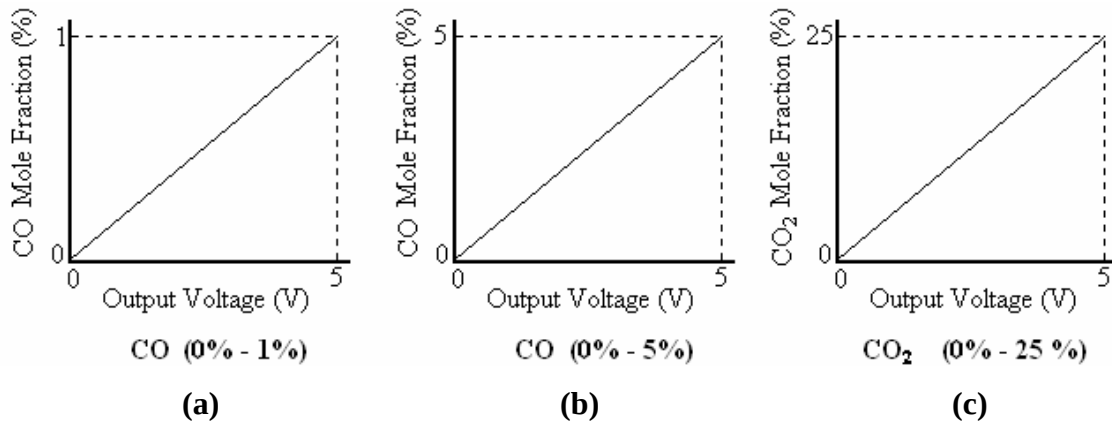


Figure 2-16: Signal conversion from volts to mole fraction for (a) CO (0%-1%), (b) CO (0%-5%) and (c) CO₂ (0%-25%).

$$X^n = \text{factor} \times \text{Volt} \quad (2-4)$$

Where,

X^n is the % mole fraction of specie.

factor is the conversion factor from Volts to % mole fraction.

Volt is the signal output voltage from the gas analyzer.

The conversion factors used by to convert the voltage into the mole fraction using Equation (2-4) are in Table 2-3.

Table 2-3: Conversion factors from volts to mole fraction for CO / CO₂ gas analyzer.

Gas	factor
CO (0%-1%)	0.2
CO (0%-5%)	1.0
CO ₂ (0%-25%)	5.0

2.1.5.2 O₂ Gas Analyzer

A Siemens paramagnetic Oxymat 5E analyzer was used to measure the O₂ mole fractions. The output signal was 4 mA to 20 mA as well. It was converted to a 0 V to 5 V signal and read by the data acquisition card. A range of 0 % to 22 % was used. The output signal was linearized with respect to O₂ mole fraction using a zero gas (Nitrogen) and a 4.71 % O₂ gas. The linearization of the signal with respect to the mole fraction is shown in Figure 2-17.

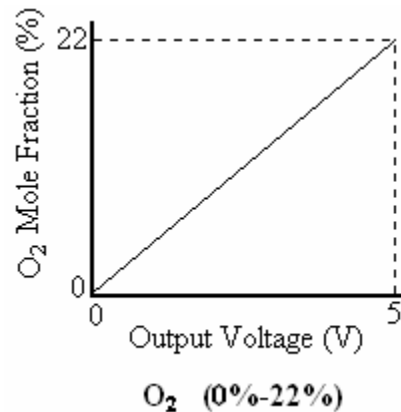


Figure 2-17: Signal conversion from volts to mole fraction for O₂ (0%-22%).

The conversion factor used in Equation (2-4) to obtain the percentage mole fraction of O₂ from the output voltage was: factor = 4.4

2.1.5.3 Unburned Hydrocarbon Measurements

A Gow-Mac model #12-800 Flame Ionization Detector (FID) was used to measure unburned hydrocarbon wet mole fractions. Signal processing was performed by a Gow-Mac model #40-900 electrometer. The FID was installed in an oven Fisher model Isotemp 500 series kept at a temperature of 105 °C. The hydrogen flame was produced by a mixture of 40 % hydrogen and 60 % helium as the fuel and purified air as the oxidant.

The flame products were vented into a cooling chamber at -10 °C containing a hydrogen detector linked to a warning light for safety reasons. The schematic of the system is shown in Figure 2-18.

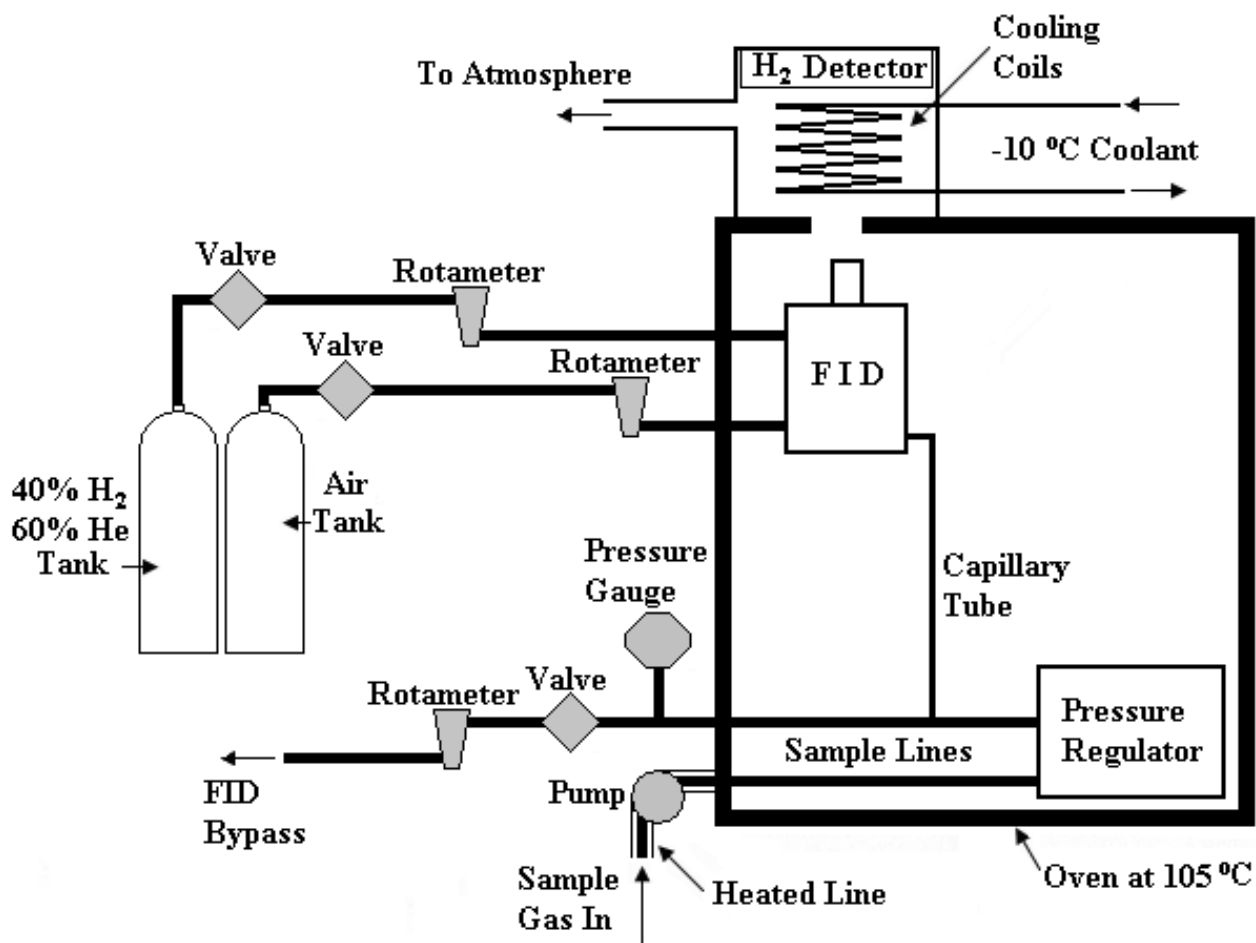


Figure 2-18: Schematic of Flame Ionization Detector.

The FID was calibrated before each test using Nitrogen (0.0% ethylene) and a 4.71% ethylene span gas. The measurements of unburned hydrocarbon were obtained as equivalent ethylene.

2.1.6 Data Acquisition System

The data from the gas analyzers, pressure transducers and mass flow meter were collected using two Data Translation, Inc. data acquisition cards, model DT303. They had a 12-bit resolution, 16 single-ended or 8 differential input channels and a PCI bus interface. Both cards were connected to external screw terminals. The differential mode was used and 16 channels were available to get data from the 3 gas analyzers, 5 pressure transducers and the mass flow meter.

Another Data Translation, Inc. data acquisition card, model DT3003/PGL was used to collect the data from the thermocouples with high gain, 12-bit resolution, 64 single-ended or 32 differential input channels and a PCI bus interface. The differential mode was used as well. The card was connected to an external screw terminal providing cold junction compensation. All the channels were linked to a panel of 32 jacks for ease of connections. This panel was attached to the frame of the hallway where extension cords for the thermocouples could be plugged in. During each experiment, data from 27 thermocouples was collected.

The data collection code was written in LABVIEW™ (Version 6.1) developed by National Instrument, Inc. Data for each of the measured values was sampled and recorded every second during the whole duration of a test. A FORTRAN code was then used to read the data file and obtain the desired results.

2.2 EXPERIMENTAL PROCEDURE

2.2.1 Equipment Calibration

Every day of experimentation began by the calibration of the gas analyzers. The data acquisition code was started and calibration data of zero and span gases was collected for each of the analyzers.

The pressure transducers were also zeroed one at a time by connecting the high and low pressure ports together, thus generating a zero pressure difference. The output voltage was monitored using a Voltmeter and the zero was adjusted to 2.5 Volts.

The fuel mass flow meter possessing a tare button was zeroed prior to opening the valves on the fuel sampling line.

2.2.2 Cleaning of Filters and Rakes

The gas sampling line filters and the aspirated thermocouples filters were then cleaned and assembled. An air compressor was used to clean each sampling probes mounted on the two rakes. Upon completion of the cleaning process, the filters were reassembled and a leak test of the sampling line was performed.

2.2.3 Leak Testing of Sampling Line and Sampling Rakes

For safety measures and to obtain meaningful results, the sampling line was leak tested. Indeed, dilution of the sampled gas with fresh air would alter the gas composition yielding to worthless results. The leak test was performed by monitoring the pressure inside the sample line after pressurizing it to 20 psig with an air compressor.

First, the sample line and filters were isolated from the rakes and a leak test was executed. If the pressure was not steady, leaks were located by the mean of soapy water applied at each connection. Leaking connections would be tightened and the leak test would be repeated.

Once the filters and sample line were leak proof, the rakes were connected to it and the same process was repeated.

2.2.4 Ignition of the Fire

Prior to the fire ignition, the two sampling pumps and thermocouple pumps were turned on to monitor the transient behavior of the flow properties. The exhaust hood was turned on as well for safety measures. The gas burner was ignited using a handheld ignition torch. The ignition torch was a propane tank connected to a three feet long ¼-inch stainless steel tube. The pilot flame was lit and the tube was inserted through a hole in the compartment ceiling. When the pilot flame was properly located on top of the burner, the main fuel line was opened and the fuel mass flow rate slowly adjusted to the desired value. The pilot flame was pulled out and the hole was plugged. The time corresponding to the ignition of the fire was recorded.

At the beginning of a test series, a warm-up period was observed. Data was not collected until temperatures within the compartment and the hallway reached steady values. Steadiness was achieved when the changes in temperatures $\Delta T/\Delta t$ would not exceed 10 K/min. The warm-up period for the first test of the day was approximately 2000s to 3000s. In order to limit the time of testing, a test series would consist of two to three tests with increasing heat release rates. This avoided any cooling down period between tests.

2.2.5 Test Procedure

The data was collected during the steady-state period of the fire at a sampling rate of 1 Hz. Measurement grids were appropriately determined, for both doorways, based on the expected spatial variations of the local flow properties.

In order to observe the degree of burning at the compartment doorway, a window was installed on the side of the hallway next to the compartment.

2.2.5.1 Doorway Mapping

For the present study, the combination of the ventilation condition was fixed (i.e.: doorway dimensions). Only the burner elevation and the fuel mass flow rate were varied.

At the compartment, a baseline doorway $W=0.33$ m wide and $H=0.82$ m high was installed. The rake shown in Figure 2-19 (a) was used and all 24 points of the measurement grid shown in Figure 2-19 (b) were investigated. Dimensions are given in meters in Figure 2-19 (a) and non-dimensionalized based on the doorway dimensions in Figure 2-19 (b). At each point, data was collected for a period of 180 seconds. The local properties for data reduction were obtained by averaging over the middle minute.

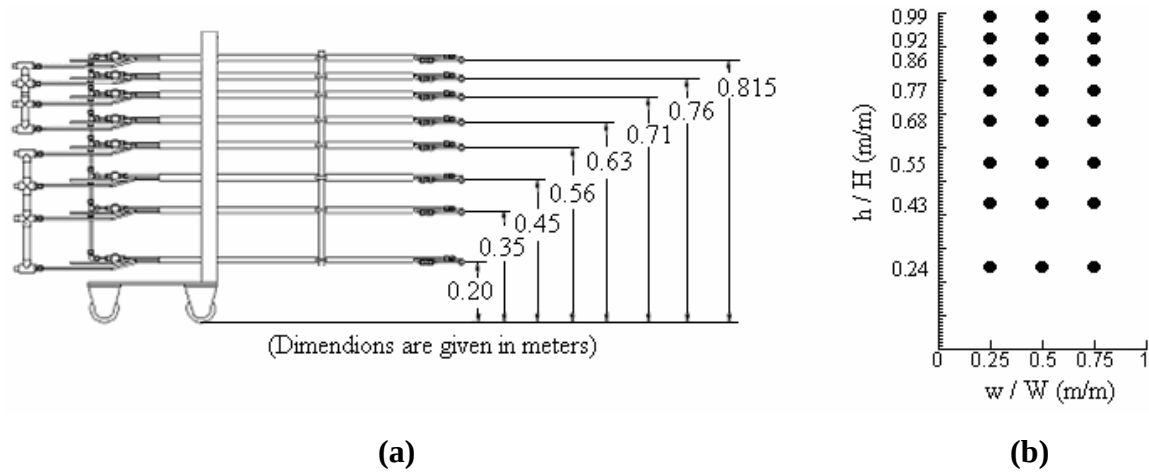


Figure 2-19: (a) Schematic of the Compartment sampling rake, (b) Measurement grid for the compartment baseline doorway.

For each horizontal location ($w/W=0.25$, $w/W=0.5$ and $w/W=0.75$), eight vertical locations were investigated ($h/H=0.99$, $h/H=0.92$, $h/H=0.86$, $h/H=0.77$, $h/H=0.68$, $h/H=0.55$, $h/H=0.43$ and $h/H=0.24$). The pressure transducer used was chosen based on the appropriate range and the sampling line was routed to the point by opening the corresponding valve. The change in the horizontal location was performed by pushing in or pulling out the sampling rake. To ensure repeatability of the measurements, data was collected more than once for some of the points upon completion of the mapping process.

At the end of the compartment doorway mapping, the sampling line was moved to the hallway end sampling rake where a narrow doorway, $W=0.165$ m wide and $H=0.82$ m high, was installed. The spatial variations expected to be lesser than at the compartment doorway, the rake shown in Figure 2-20 (a) was used and all five points of the measurement grid, Figure 2-20 (b), were investigated. The same period of 180 seconds was used to collect data at each point.

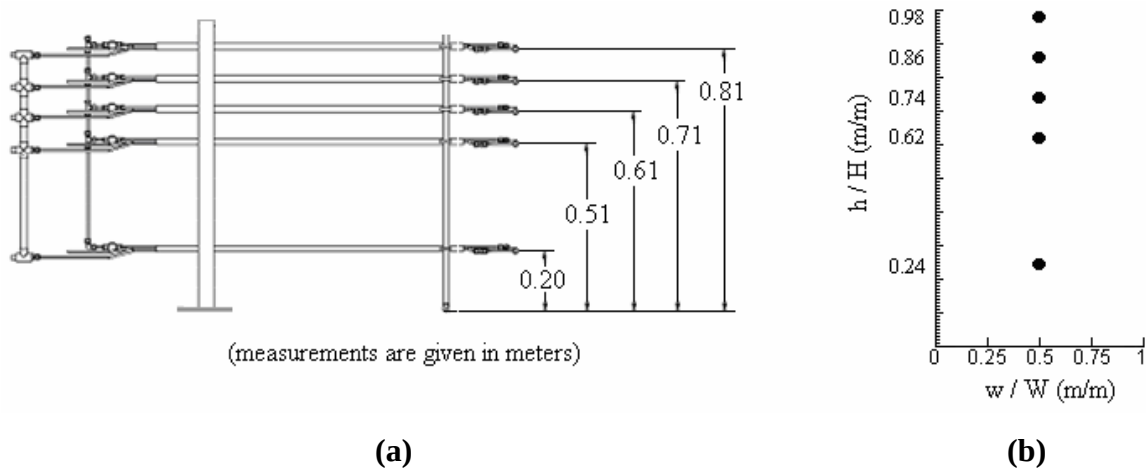


Figure 2-20: (a) Schematic of the Hallway end sampling rake b) Measurement grid for hallway-exit narrow doorway.

The rake was fixed at one horizontal location ($w/W=0.5$) and the same procedure than for the compartment doorway mapping was used to collect data at the five vertical locations ($h/H=0.98$, $h/H=0.86$, $h/H=0.74$, $h/H=0.62$ and $h/H=0.24$).

2.2.5.2 Visual Observation

A Pyrex window located on the side of the hallway next to the compartment doorway allowed the observation of the fire. The doorway was observed for a period of 10 minutes and the degree of burning at the compartment doorway was determined. The presence of occasional flamelets or consistent external burning depending on the test was noted.

To allow qualitative comparison of the smoke layer depth developed along the hallway, pictures were taken at the end of each test. The best position of the camera, angle of shooting and lighting was determined and reproduced for each case studied.

2.3 DATA REDUCTION CALCULATIONS AND PROCEDURES

2.3.1 Local Average Properties

The diagram, Figure 2-21, shows the steps followed by the data reduction code to obtain the local average properties at each sampled points.

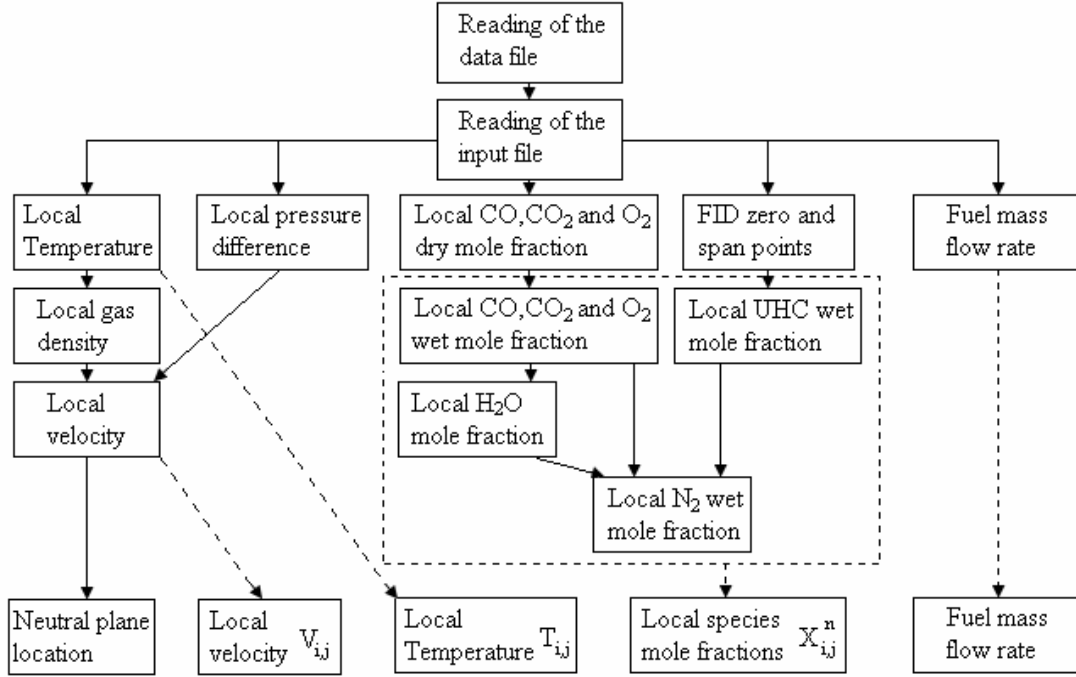


Figure 2-21: Diagram for local properties calculations (subscripts i and j refer to the location on the grid of the sampling point)

2.3.1.1 Local Wet Species Mole Fractions

The non-dispersive infrared CO/CO₂ and paramagnetic O₂ analyzers worked on a dry gas basis. The mole fractions of CO, CO₂ and O₂ measured had to be corrected for water content. The subscript or superscript n refers to the specie being considered (i.e., CO, CO₂, O₂, N₂, H₂O or UHC).

From the definition of the dry mole fraction,

$$\frac{N_n}{N_{\text{tot,dry}}} = X_{\text{dry}}^n \quad (2-5)$$

To correct for water content, the number of moles of H_2O , N_{H_2O} must be added to the total number of moles of dry gas, $N_{tot,dry}$ to obtain the total number of moles of wet gas, $N_{tot,wet}$.

$$N_{tot,wet} = N_{tot,dry} + N_{H_2O}$$

Dividing both sides by $N_{tot,wet}$ yields to,

$$\frac{N_{tot,dry}}{N_{tot,wet}} = 1 - X_{wet}^{H_2O} \quad (2-6)$$

And substituting $N_{tot,dry}$ from Equation (2-5) into Equation (2-6),

$$\frac{N_n}{N_{tot,wet}} = (1 - X_{wet}^{H_2O}) X_{dry}^n$$

The following formula is obtained to correct the dry moles fractions measured for the water content.

$$X_{wet}^n = (1 - X_{wet}^{H_2O}) X_{dry}^n \quad (2-7)$$

In order to calculate the wet species concentration, the H_2O mole fraction, X^{H_2O} , must be known. Since it is hard to measure water concentration, previous investigators [Gottuk 1992, Ewens 1994, Lattimer 1996, McKay 2002, Wieczorek 2002] assumed the molar ratio, c , of H_2O to CO_2 at any equivalence ratio to be equal to the calculated molar ratio at stoichiometric conditions.

From the stoichiometric reaction of propane,



The stoichiometric molar ratio of H_2O to CO_2 is calculated:

$$c = \frac{X_{wet}^{H_2O}}{X_{wet}^{CO_2}} = \frac{4}{3} \quad (2-8)$$

So Equation (3-7) applied to CO₂,

$$X_{\text{wet}}^{\text{CO}_2} = (1 - X^{\text{H}_2\text{O}}) X_{\text{dry}}^{\text{CO}_2}$$

And substituting in Equation (2-8),

$$c = \frac{X^{\text{H}_2\text{O}}}{(1 - X^{\text{H}_2\text{O}}) X_{\text{dry}}^{\text{CO}_2}}$$

Rearranging gives:

$$1 - X^{\text{H}_2\text{O}} = \frac{1}{1 + c \times (X_{\text{dry}}^{\text{CO}_2})}$$

The wet species molecular concentrations can then be calculated from,

$$X_{\text{wet}}^n = \frac{X_{\text{dry}}^n}{1 + \frac{4}{3} \times (X_{\text{dry}}^{\text{CO}_2})} \quad (2-9)$$

2.3.1.2 Local Wet N₂ Mole Fraction

The local wet N₂ mole fraction was obtained with the assumption that only carbon monoxide, carbon dioxide, oxygen, unburned hydrocarbons and water are generated from the fire. The temperature within the compartment not being high enough for significant levels of nitric oxides (NO_x) to be generated, are omitted. Thus, the sum of mole fractions of all the species present must be equal to unity.

$$X_{\text{wet}}^{\text{N}_2} = 1 - (X_{\text{wet}}^{\text{O}_2} + X_{\text{wet}}^{\text{CO}_2} + X_{\text{wet}}^{\text{CO}} + X_{\text{wet}}^{\text{UHC}} + X_{\text{wet}}^{\text{H}_2\text{O}})$$

2.3.1.3 Local Temperature

The local temperature was obtained at each point of sampling using type K thermocouples. To measure the temperature of the gas so close to the fire required eliminating any heat transferred to the thermocouples via radiation from the fire. They were shielded and gas was aspirated using pumps.

2.3.1.4 Local velocity

The local velocity calculations required the local gas density to be estimated. It was obtained from the ideal gas law. The static pressure was obtained prior to each test from the local weather forecast. The gas molecular weight was also assumed to be constant and equal to that of air (MW=28 g/mol). The local density was then only a function of the local temperature and was calculated from Equation (2-10).

$$\rho = \frac{P_{\text{atm}} MW_{\text{air}}}{R_u T} = \frac{P_{\text{atm}} \times 28.95}{8314} \times \frac{1}{T} = \frac{P_{\text{atm}} \times 28.95}{8314 \times T} \quad \left[\frac{\text{kg}}{\text{m}^3} \right] \quad (2-10)$$

The velocity was obtained at each sampled points using Equation (2-11)

$$V = 0.070 \sqrt{T \Delta P} \quad \left[\frac{\text{m}}{\text{s}} \right] \quad (2-11)$$

2.3.2 Neutral Plane Location

The neutral plane height was determined for each velocity profiles (one for each w/W horizontal location of sampling). The velocities measured directly above and below the neutral plane location were used. A linear interpolation between these two points was performed. The neutral plane height was then obtained by solving for the height corresponding to a zero velocity. Depending on the rake used and the test, the neutral plane was located between different probes. This is illustrated in Figure 2-22.

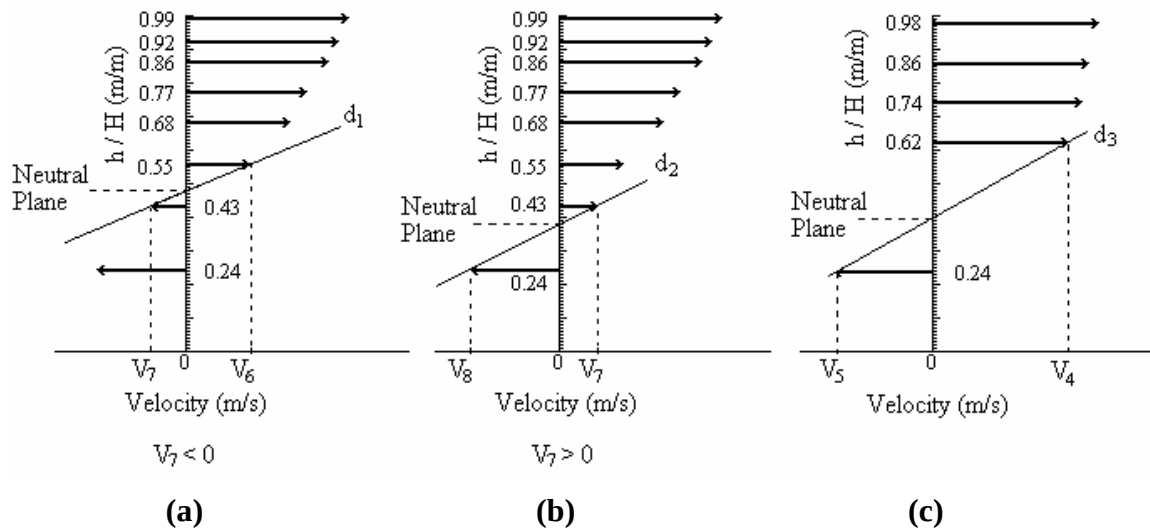


Figure 2-22: Different cases of velocity profiles at a fixed w/W location for the compartment doorway (a) if $V_7 < 0$, (b) if $V_7 > 0$ and (c) the hallway doorway.

Since no measurements were taken at the doorway boundaries, the local properties along the doorway edges were assumed to be equal to the nearest measured point. The velocity was set to zero at the neutral plane.

2.3.3 Integrated Mass Flow Rates through the Doorways

The methodology used to calculate the mass flow rates over the inflow and outflow regions of the doorways is based on the local velocities, local temperatures, and local species mole fractions measurements across the doorways.

The neutral plane location calculation was used to determine the boundaries of the outflow and the inflow regions. Each species mass flow rates were calculated separately over both regions. The subscript i and j are the horizontal and vertical location of the sampling point. The superscript n corresponds to the species being considered.

The local species mass fractions can be obtained from,

$$y_{i,j}^n = X_{i,j}^n \frac{MW^n}{MW_{i,j}^{mix}} \quad (2-12)$$

With a local mixture molecular weight,

$$MW_{i,j}^{mix} = \sum_n X_{i,j}^n MW^n$$

The local density of each species was obtained from the measured local temperature and the atmospheric pressure (101325 Pa) using Equation (2-13).

$$\rho_{i,j}^n = \frac{P MW^n}{R_U T_{i,j}} = \frac{12.19 \frac{\text{kg K}}{\text{m}^3} MW^n}{T_{i,j}} \quad (2-13)$$

So each species mass flow rate could be obtained from equation,

$$\dot{m}^n = \iint_A y_{i,j}^n \rho_{i,j}^n V dA$$

Or,

$$\dot{m}^n = \iint_A X_{i,j}^n \frac{MW^n}{MW_{i,j}^{mix}} \rho_{i,j}^n V dA \quad (2-14)$$

Equation (2-14) can be rewritten for the inflow and outflow species mass flow rates with the subscripts i and j substituted by their corresponding h (height) and w (width) coordinates (h_{NP} , H and W are the neutral plane height, the doorway height and the doorway width respectively).

$$\dot{m}_{out}^n = \int_0^W \int_{h_{NP}}^H X^n(h, w) \frac{MW^n}{MW^{mix}(h, w)} \rho^n(h, w) V dh dw \quad (2-15)$$

$$\dot{m}_{in}^n = \int_0^W \int_0^{h_{NP}} X^n(h, w) \frac{MW^n}{MW^{mix}(h, w)} \rho^n(h, w) V dh dw \quad (2-16)$$

Equations (2-15) and (2-16) were solved numerically (using a double trapezoidal rule) for each species.

The total mass flow rates through both regions were then calculated by summing up all the individual species mass flow rates.

$$\dot{m}_{out} = \sum_n \dot{m}_{out}^n \quad (2-17)$$

$$\dot{m}_{in} = \sum_n \dot{m}_{in}^n \quad (2-18)$$

2.3.4 Integrated Species Mass Fractions

The integrated species mass fractions over the outflow and inflow regions were obtained from the calculated integrated mass flow rates.

$$\bar{y}_{out}^n = \frac{\dot{m}_{out}^n}{\dot{m}_{out}} \quad (2-19)$$

$$\bar{y}_{in}^n = \frac{\dot{m}_{in}^n}{\dot{m}_{in}} \quad (2-20)$$

2.3.5 Inflow Mass Flow Rates – Mass Balance

Depending on the neutral plane location (Figure 2-22), a limited number of points were sampled at in the inflow region of the doorways. In order to obtain a more accurate measurement of the inflow mass flow rate, (i.e., air entrainment rate into the compartment), a mass balance was performed. For the compartment doorway, the mass balance was performed on the compartment. For the hallway doorway, the control volume considered was the combination of the compartment and the hallway.

$$\dot{m}_{in,Bal} = \dot{m}_{out} - \dot{m}_{fuel} \quad (2-21)$$

The individual species mass flow rates over the inflow region were recalculated using the average species mass fraction and the total inflow mass flow rate based on the mass balance.

$$\dot{m}_{in}^n = \dot{m}_{in,bal}^n = \bar{y}_{in}^n \dot{m}_{in,bal} \quad (2-22)$$

A diagram of the calculation performed by the data reduction code to obtain the data required for further analysis is shown in Figure 2-23.

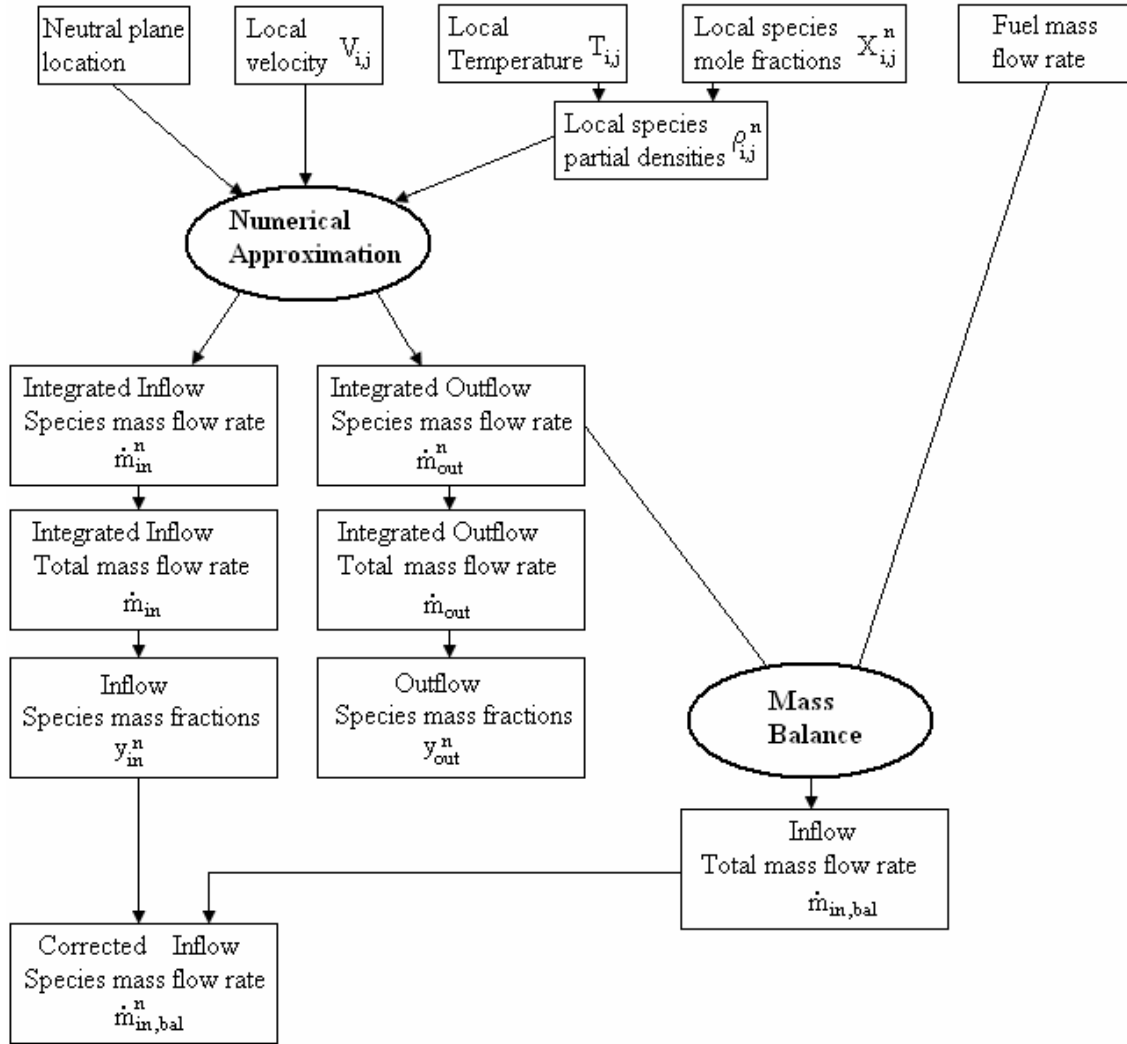


Figure 2-23: Diagram of the calculations (subscripts i and j refer to the location on the grid of the sampling point, Superscript n refers to the specie considered).

2.3.6 Species Yields

The quantification of species generation in a fire is usually defined in terms of species yield. The specie yield, for combustion products, is the ratio of the mass of the specie produced to the mass of fuel burnt. (The mass per unit time can also be used).

$$Y^n = \frac{m_{\text{produced}}^n}{m_{\text{fuel}}} = \frac{\dot{m}_{\text{produced}}^n}{\dot{m}_{\text{fuel}}}$$

The produced mass flow rate of specie can be obtained by performing a specie mass balance over the compartment.

$$\dot{m}_{\text{produced}}^n = \dot{m}_{\text{out}}^n - \dot{m}_{\text{in}}^n$$

So the species yields can be expressed as,

$$Y^n = \frac{\dot{m}_{\text{out}}^n - \dot{m}_{\text{in}}^n}{\dot{m}_{\text{fuel}}} \quad (2-23)$$

For oxygen which is being consumed and not produced, another definition of the yield must be used. The oxygen yield is defined as the ratio of the mass of oxygen consumed to the mass of fuel burnt. (The mass per unit time can also be used).

$$Y^{O_2} = \frac{m_{\text{consumed}}^{O_2}}{m_{\text{fuel}}} = \frac{\dot{m}_{\text{consumed}}^{O_2}}{\dot{m}_{\text{fuel}}}$$

Since not all the oxygen entering the compartment is consumed, the mass flow rate of oxygen consumed by the fire can be obtained from an oxygen mass balance over the compartment.

$$\dot{m}_{\text{consumed}}^{O_2} = \dot{m}_{\text{in}}^{O_2} - \dot{m}_{\text{out}}^{O_2}$$

And the oxygen yield is then,

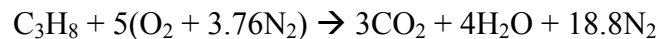
$$Y^{O_2} = \frac{\dot{m}_{\text{in}}^{O_2} - \dot{m}_{\text{out}}^{O_2}}{\dot{m}_{\text{fuel}}} \quad (2-24)$$

Normalizing the yields of carbon dioxide and oxygen based on their theoretical maximum yields provide an indicator of the degree of completeness of the combustion.

$$f^n = \frac{Y^n}{Y_{\text{theory}}^n} \quad (2-25)$$

The theoretical maximum yields are the mass of a species produced or consumed by stoichiometric combustion of one mole of fuel.

From the stoichiometric reaction for propane,



$$Y_{\text{theory}}^{\text{CO}_2} = \frac{N^{\text{CO}_2} \times \text{MW}^{\text{CO}_2}}{N^{\text{C}_3\text{H}_8} \times \text{MW}^{\text{C}_3\text{H}_8}} = \frac{3 \times 44}{1 \times 44} = 3 \text{ (g / g}_{\text{fuel}} \text{)} \quad (2-26)$$

$$Y_{\text{theory}}^{\text{O}_2} = \frac{N^{\text{O}_2} \times \text{MW}^{\text{O}_2}}{N^{\text{C}_3\text{H}_8} \times \text{MW}^{\text{C}_3\text{H}_8}} = \frac{5 \times 32}{1 \times 44} = 3.64 \text{ (g / g}_{\text{fuel}} \text{)} \quad (2-27)$$

$$Y_{\text{theory}}^{\text{CO}} = \frac{N^{\text{CO}} \times \text{MW}^{\text{CO}}}{N^{\text{C}_3\text{H}_8} \times \text{MW}^{\text{C}_3\text{H}_8}} = \frac{3 \times 28}{1 \times 44} = 1.91 \text{ (g / g}_{\text{fuel}} \text{)} \quad (2-28)$$

The normalized yields range between 0 and 1.0 where 1.0 represents complete combustion.

2.3.7 Ideal Heat Release Rate

Assuming that all the fuel is burnt in the compartment, the ideal heat release rate of the fire is determined by,

$$\dot{Q}_{\text{ideal}} = \dot{m}_{\text{fuel}} \Delta H_c \quad (2-28)$$

For propane, the enthalpy of combustion ΔH_c is:

$$\Delta H_c = 46300 \left[\frac{\text{kJ}}{\text{kg}} \right]$$

However, ΔH_c assumes stoichiometric combustion which would result in the generation of products of complete combustion only (i.e., no carbon monoxide).

CHAPTER 3 – A PARAMETRIC STUDY OF THE EFFECT OF FIRE SOURCE ELEVATION ON CO LEVELS LEAVING A COMPARTMENT

3.1 MOTIVATIONS FOR THE FIRE SOURCE ELEVATION STUDY

This research is the continuation of the study conducted by Wieczorek [2003]. To decide on the parameter to study, careful considerations of existing results obtained in the study of the half-scale ISO 9705 compartment, with and without the hallway, were taken. The results of carbon monoxide yields as a function of the non-dimensional heat release rate parameter, developed by Wieczorek [2003], are presented in Figure 1-7. Illustrations of the fire corresponding to different values of $\tilde{Q}$ are shown in Figure 3-1 to help visualize and understand the combustion process leading to the CO yields observed.

In Figure 3-1 (a) and (b), the fire is contained inside the compartment ($\tilde{Q} < 1$). For these scenarios, low levels of carbon monoxide were measured. Sufficient amount of air was entrained by buoyancy along the fire plume to result in the complete combustion of the fuel, even if some of the fuel was burnt within the upper layer (Figure 3-1 (b)).

Figure 3-1 (c) represents the stage at which the flame tip reached the top of the doorway, and by definition, $\tilde{Q} = 1$. The levels of carbon monoxide measured were still very low indicating a complete combustion that implied sufficient oxygen availability. The absence of measurements within the compartment prevents any assured statements to be made on the air entrainment patterns. There are two possible ways for the oxygen to be provided to the unburned fuel present in the upper layer. The first one is from the air entrained along the fire plume and the second is directly entrained into the upper layer by mixing between the cold layer and the hot (upper) layer. The most plausible scenario would be that the oxygen was provided in sufficient quantity to the fuel by a combination of these two paths.

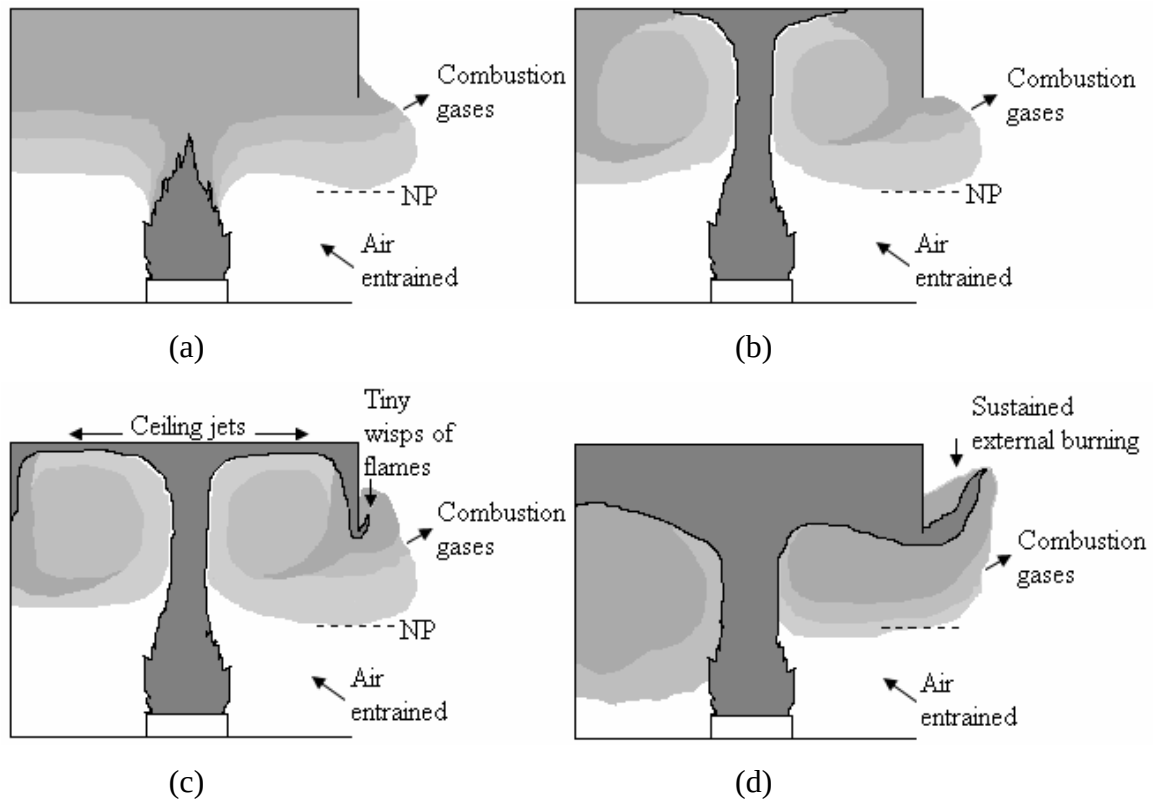


Figure 3-1: Representation of the fire dynamic for four $\tilde{Q}$ conditions (a) $\tilde{Q} < 1.0$ with fire below upper layer, (b) $\tilde{Q} < 1.0$, (c) $\tilde{Q} = 1.0$, (d) $1.25 < \tilde{Q} < 3.5$.

In Figure 3-1 (d), most of the fuel is being burnt within the upper layer. External burning is sustained ($\tilde{Q} > 1$). Wieczorek [2003] reported that carbon monoxide yields began to increase for values $\tilde{Q} > 1.25$ signifying that the fuel was not burning at stoichiometric conditions. However, when presented as a function of the equivalence ratio, the increase in CO yield occurred independently for each doorway at values of $\phi < 1$. This shows that, although enough air was entrained through the doorway, the combustion is not complete.

A change in the dynamic of the fire within the compartment must occur for $1 < \tilde{Q} < 1.25$. One conceivable explanation would be to consider the upper-layer as a poorly-mixed and fuel-rich reactor in which the combustion is incomplete. Once the

change happens, additional fuel will only worsen the degree of mixing and contribute to the increase in CO yields and other products of incomplete combustion.

A plateau was observed by Wieczorek [2003] for values of $\tilde{Q} > 3.5$ and should be seen as a limit due to geometrical parameters such as the compartment size, the soffit depth, the doorway width and the burner elevation.

Although no data was obtained for higher values of $\tilde{Q}$, Wieczorek [2003] suggested that a decrease in the CO, CO₂ and depleted O₂ yields, tending to zero, was expected.

This suggestion would imply no burning inside the compartment. The unburned hydrocarbon yields would increase to infinity and only fuel would be present inside the compartment. The compartment transformed into the plenum of a burner, the doorway cross-section would become a vertical fire source.

This scenario was actually observed by Wieczorek [2003] for the doorway termed the sliver doorway. The sliver doorway width was half the width of the narrow doorway (0.08 m). The ventilation area of 0.06 m² was then smaller than the burner area of 0.07 m².

In Figure 3-2a, air was entrained through the lower 1/3 portion of the doorway while flames extended out of the compartment through the upper 2/3 portion. Wieczorek [2003] reported that the transition from the flame structure shown in Figure 3-2a to the one shown in Figure 3-2b occurred 3 to 4 hours after the beginning of the test. The flame structure shown in Figure 3-2b corresponds to the scenario described previously when the doorway becomes the burner.

This scenario was observed during the transport study performed by Wieczorek [2003] with the hallway connected to the compartment. No hallway doorway and soffit were installed at the hallway exit. For this test, an ideal heat release rate of 130 kW was

studied and 3 cross-sections mappings were performed along the hallway involving a long test duration allowing this transition to occur.

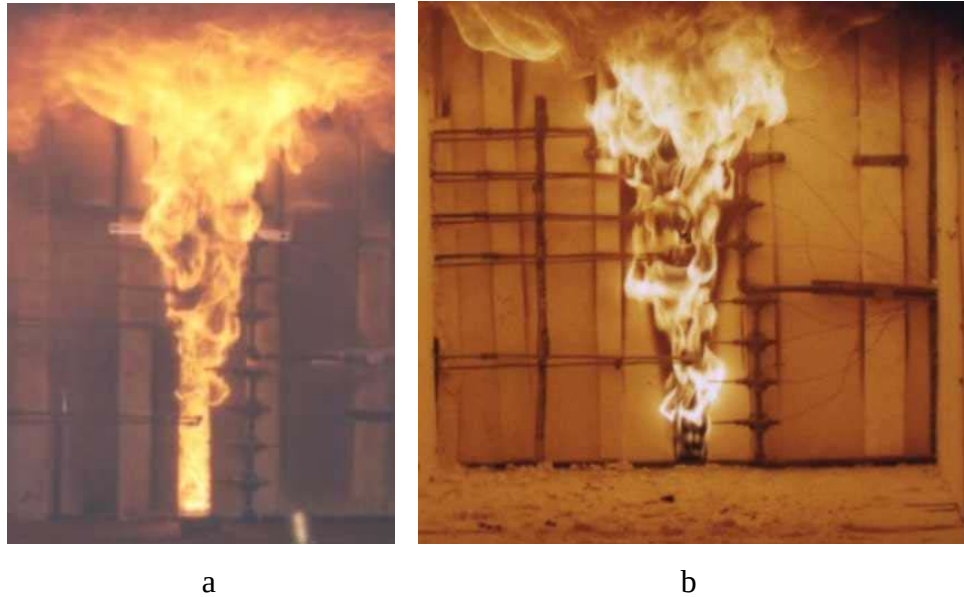


Figure 3-2: Flame structure at the compartment/hallway interface for a sliver doorway for ideal heat release rate, $\dot{Q}_{ideal} = 130$ (kW) (Picture taken from Wieczorek [2003])

During the compartment study performed by Wieczorek [2003] on the sliver doorway, tests durations were shorter and no such transition was reported for even higher ideal heat release rate (up to 300 kW). Moreover, the compartment study of the sliver doorway showed high carbon monoxide integrated mole fractions combustion inside the compartment. Although no data is available from long duration tests for the compartment study in the stand alone configuration, the occurrence of this transition is expected introducing steady state issues. Not representing the same fire scenario as the other three doorways, the compartment study of the sliver doorway was reported separately.

From the work conducted by Wieczorek [2003], the following observations were made:

- When the fire is contained within the compartment, the air entrained through the doorways exceeds the amount required for stoichiometric reaction for all three doorway studied.

- None or very little carbon monoxide is formed from the fuel burning below the upper-layer.
- At a certain value of fuel mass flow rate, specific to the geometric parameters, the upper layer becomes a poorly-mixed and fuel-rich reactor in which the combustion is incomplete. This change in the fire dynamic is believed to be due to the oxygen deficiency in the upper layer and a lack of mixing. Once the change happens, the levels of CO rise rapidly with small increase in fuel mass flow rate.
- The species levels produced are directly related to the air entrainment pattern, the upper layer mixing pattern and the location of the reaction.
- The carbon monoxide levels reach a maximum value for a non dimensional heat release rate of $\tilde{Q}=3.5$. It then decrease as the ideal heat release rate is increased
- The species yields for values of $\tilde{Q}$ going to infinity are expected to decrease and tend to 0.

The study of the burner elevation was proposed in order to confirm these observations. However, this research was performed for the compartment with a hallway in a head-on configuration and not for the compartment in the stand-alone configuration, making the comparison more difficult.

Positioning the burner surface closer to the upper-layer, for a fixed fuel mass flow rate, changes the dynamic of the fire within the compartment. To investigate the effects of the burner elevation on the species production, three burner elevations were examined. The top surface of the burner was used to define the elevation of the fire source. The first elevation corresponded to the burner laid on the floor, $h/H_{Door}=12.5\%$, the second and the third were respectively, $h/H_{Door}=50\%$ and $h/H_{Door}=75\%$.

Chapter 3. A Parametric Study of the Effect of Fire Source Elevation on CO Levels Leaving a Compartment

In real fire scenarios, the fire propagates within the room. If the room is not well ventilated, the smoke builds up and most of the combustion occurs within a vitiated gas, increasing the production of CO. Elevated objects such as shelves, posters and curtains could ignite in the early stage of a fire. The flames would be burning within the upper layer of combustion gas producing high levels of CO and increasing the risks of intoxication for people in remote locations.

In this chapter, the results obtained at the compartment doorway are presented. The transport study along the hallway is discussed in Chapter 4. The present analysis was performed to study the effects of the burner elevation on the composition of the combustion products. The objective of this study was to investigate how the location of the combustion reaction impacted the species generation. It was observed from preliminary testing that as more of the combustion occurred within the upper layer the levels of carbon monoxide increased.

3.2 PRESENTATION OF THE RESULTS

3.2.1 Test Matrix

Three burner heights were investigated. For the purpose of solely studying the effects of the burner elevation, the ventilation conditions were fixed. A baseline doorway (0.33 m wide) was installed at the compartment and a narrow doorway (0.165 m wide) at the hallway exit. Only the cases where the fire was contained inside the compartment were of interest in this study.

For all three burner heights, the ideal fire size was increased until the maximum carbon monoxide levels were observed.

One test for each burner elevation corresponded to an ideal heat release rate larger than the one corresponding to the maximum CO yields. Only the results for the other 16 tests are discussed in the next sections.

Table 3-1: Burner elevation study test matrix

Test Number	Burner Elevation	Fuel Mass Flow Rate (kg/s)	Fire Size (kW)
0303210	12.50%	1.79E-03	83
0211220	12.50%	1.91E-03	89
0303211	12.50%	2.70E-03	125
0303212	12.50%	3.19E-03	148
0303213*	12.50%	3.47E-03	160
0409110	50%	6.14E-04	28
0409130	50%	7.41E-04	34
0409131	50%	1.07E-03	49
0409132	50%	1.19E-03	55
0311181	50%	1.33E-03	61
0409111*	50%	1.47E-03	68
0408250	75%	4.79E-04	22
0406090	75%	5.72E-04	26
0408251	75%	6.08E-04	28
0408252	75%	7.61E-04	35
0408253	75%	9.05E-04	41
0408310	75%	9.30E-04	43
0406220	75%	9.97E-04	46
0408311*	75%	1.12E-03	52

* Results not reported in this chapter

3.2.2 Air Entrained Into the Compartment

The air entrainment mass flow rates into the compartment doorway and into the hallway doorway were obtained following the procedure described in section 2.3. Figure 3-3 shows the air mass flow rate entrained into the compartment as a function of the ideal heat release rate for the tests listed in Table 3-2. For all cases, the fire was over ventilated ($\phi < 1$). To visualize the excess of air entrained inside the compartment, the air required for a stoichiometric reaction was calculated, Equation 3-1.

For propane, the fuel to air mass flow rate ratio required for a stoichiometric reaction is equal to 0.064.

$$\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air}}} \right)_s = 0.064$$

And

$$\dot{m}_{\text{fuel}} = \frac{\dot{Q}_{\text{ideal}}}{\Delta H_c}$$

Therefore, the amount of air required inside the compartment for the fuel to burn completely is,

$$(\dot{m}_{\text{air}})_s = \frac{\dot{Q}_{\text{ideal}}}{0.064 \Delta H_c} \quad (3-1)$$

The ventilation limits for both doorways were also calculated using the well known Equation 3-2, and added to Figure 3-3 to examine the effect of the doorway size on the air entrainment. The values are shown in Table 3-3.

$$\dot{m}_{\text{air}}^{\text{vent limit}} = 0.52 A \sqrt{H_{\text{door}}} \quad (3-2)$$

Table 3-3: Maximum air entrainment mass flow rate through the doorways

Doorway	$\dot{m}_{\text{air}}^{\text{vent limit}}$ (kg/s)
Baseline	6.178E-02
Narrow	1.274E-01

For all cases, the air entrainment mass flow rate into the compartment was significantly higher than the mass flow rate of air required for the fuel to burn at stoichiometric conditions. The observed values were much lower than the calculated ventilation limit $\dot{m}_{\text{air}}^{\text{vent limit}}$ of the baseline doorway installed at this location.

Figure 3-3 shows no dependency of the air entrainment mass flow rates to either the ideal heat release rate or the burner elevation.

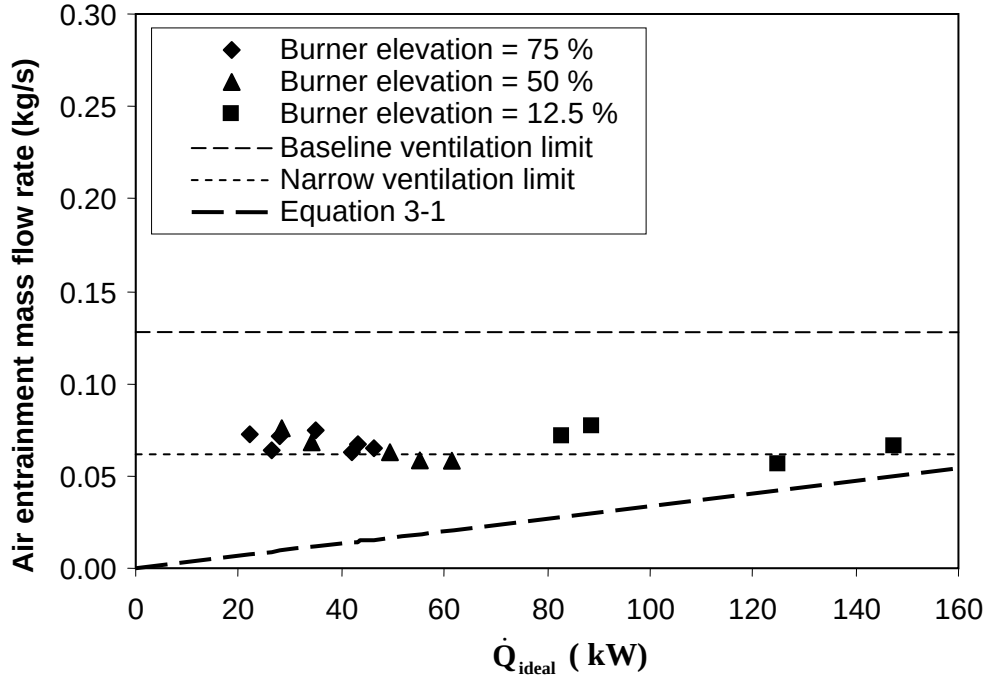


Figure 3-3: Air entrainment mass flow rate through the compartment doorway as a function of the ideal heat release rate $\dot{Q}_{ideal}$.

3.2.3 Integrated Average Species Mole Fractions versus the Ideal Heat Release Rate

Integrated average species mole fractions were obtained following the calculations described in Section 2.4. Figure 3-4 to Figure 3-6 show respectively the mole fractions of carbon monoxide, carbon dioxide, depleted oxygen (between inflow and outflow) as a function of the ideal heat release rate, $\dot{Q}_{ideal}$. The calculated mole fractions of unburned hydrocarbon were all below the accuracy of the FID analyzer and were considered equal to 0. These results represent the composition of the combustion gas flowing out of the compartment doorway.

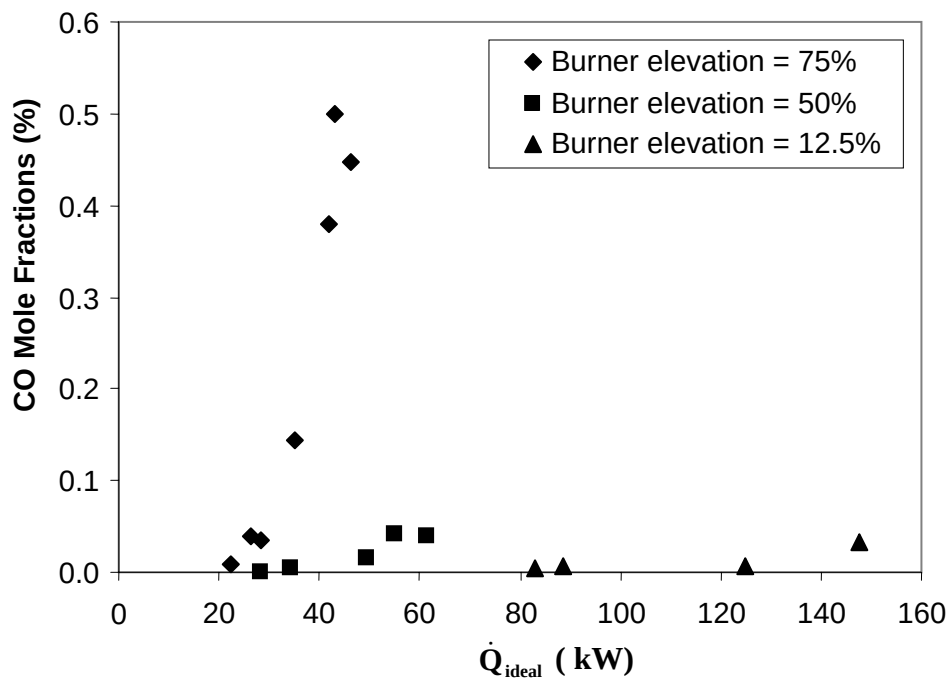


Figure 3-4: Integrated average carbon monoxide mole fractions (%) as a function of the ideal heat release rate, $\dot{Q}_{ideal}$ (kW).

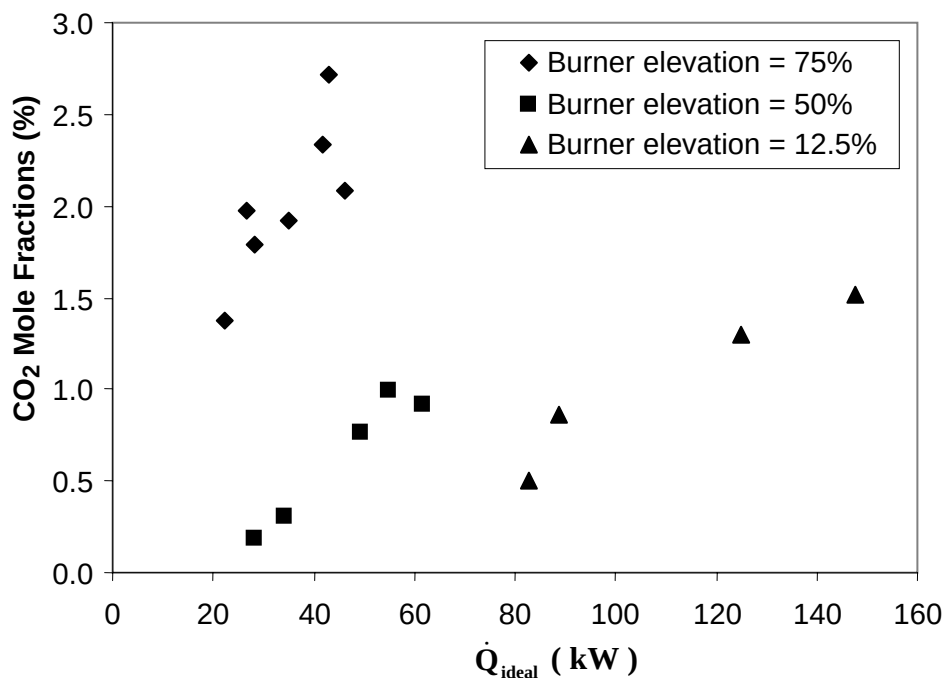


Figure 3-5: Integrated average carbon dioxide mole fractions (%) as a function of the ideal heat release rate, $\dot{Q}_{ideal}$ (kW).

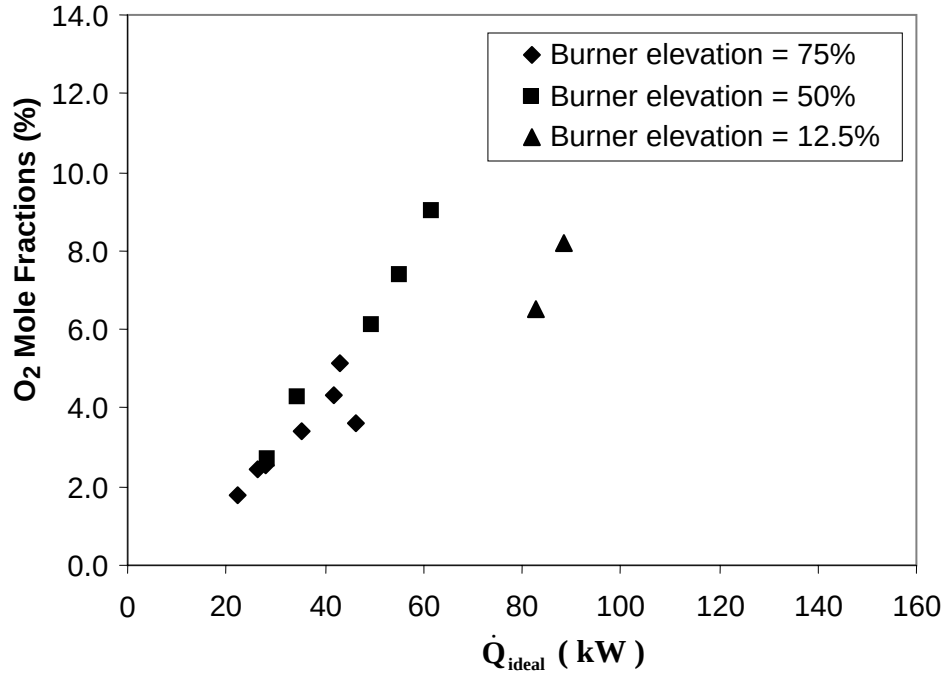


Figure 3-6: Integrated average depleted oxygen mole fractions (%) as a function of the ideal heat release rate, $\dot{Q}_{ideal}$ (kW).

For all species considered (CO, CO₂ and O₂), three distinctive curves, corresponding to the three burner elevations, can be observed. The molar concentration of carbon monoxide, carbon dioxide and depleted oxygen all increase with increasing ideal heat release rate.

To represent the species production rate, the species yields were calculated and the results are presented in the next section.

3.2.4 Species Yields versus the Ideal Heat Release Rate

The limited amount of sampling points across the compartment doorway exit plane and the averaging and integration process discussed in Section 2.4 are sources of inaccuracy. The calculation of species yields implies the comparison of species mass flow rates obtained by this process to the fuel mass flow rate measured with an accurate mass flow meter. In order to have meaningful values of species yields, the fuel mass flow

rate must be recalculated based on the oxygen depletion measured the same way as all other species.

Equation 3-3, taken from Drysdale [2001], gives the ideal heat release rate within the compartment as a function of the oxygen consumed:

$$\dot{Q}_{\text{comp}} = (0.21 - X_{\text{out}}^{\text{O}_2, \text{Scrubbed}}) \rho_{\text{O}_2} \Delta H_{\text{c,ox}} \dot{V} \quad (3-3)$$

For the present study, this equation had to be corrected for the composition of the inflowing gas. Indeed, the composition could not be assumed to be that of air anymore due to mixing along the hallway and recirculation of the exhaust gases.

$$\dot{Q}_{\text{comp}} = (X_{\text{in}}^{\text{O}_2, \text{Scrubbed}} - X_{\text{out}}^{\text{O}_2, \text{Scrubbed}}) \rho_{\text{O}_2} \Delta H_{\text{c,ox}} \dot{V} \quad (3-4)$$

In Equation 3-4, $X_{\text{in}}^{\text{O}_2, \text{Scrubbed}}$ and $X_{\text{out}}^{\text{O}_2, \text{Scrubbed}}$ are the mole fraction of oxygen in the scrubbed inflow and outflow gases respectively. “The process of scrubbing removes products of combustion from the flow of gas which is supplied continuously to the oxygen analyzer...” [Drysdale 2001] Since no scrubbing of the combustion products was performed on the gas prior to analysis, the correct oxygen mole fraction was obtained using the conservation of mass.

$$\begin{aligned} \bar{y}_{\text{out}}^{\text{O}_2, \text{Scrubbed}} &= \bar{y}_{\text{out}}^{\text{O}_2} \left(\frac{\dot{m}_{\text{out}}}{\dot{m}_{\text{out}} - (\dot{m}_{\text{out}}^{\text{CO}} + \dot{m}_{\text{out}}^{\text{CO}_2} + \dot{m}_{\text{out}}^{\text{UHC}})} \right) = \bar{y}_{\text{out}}^{\text{O}_2} \left(\frac{\dot{m}_{\text{out}}}{\dot{m}_{\text{out}} - (\bar{y}_{\text{out}}^{\text{CO}} \dot{m}_{\text{out}} + \bar{y}_{\text{out}}^{\text{CO}_2} \dot{m}_{\text{out}} + \bar{y}_{\text{out}}^{\text{UHC}} \dot{m}_{\text{out}})} \right) \\ \bar{y}_{\text{out}}^{\text{O}_2, \text{Scrubbed}} &= \bar{y}_{\text{out}}^{\text{O}_2} \left(\frac{1}{1 - (\bar{y}_{\text{out}}^{\text{CO}} + \bar{y}_{\text{out}}^{\text{CO}_2} + \bar{y}_{\text{out}}^{\text{UHC}})} \right) \end{aligned}$$

and

$$\begin{aligned} \bar{y}_{\text{in}}^{\text{O}_2, \text{Scrubbed}} &= \bar{y}_{\text{in}}^{\text{O}_2} \left(\frac{\dot{m}_{\text{in}}}{\dot{m}_{\text{in}} - (\dot{m}_{\text{in}}^{\text{CO}} + \dot{m}_{\text{in}}^{\text{CO}_2} + \dot{m}_{\text{in}}^{\text{UHC}})} \right) = \bar{y}_{\text{in}}^{\text{O}_2} \left(\frac{\dot{m}_{\text{in}}}{\dot{m}_{\text{in}} - (\bar{y}_{\text{in}}^{\text{CO}} \dot{m}_{\text{in}} + \bar{y}_{\text{in}}^{\text{CO}_2} \dot{m}_{\text{in}} + \bar{y}_{\text{in}}^{\text{UHC}} \dot{m}_{\text{in}})} \right) \\ \bar{y}_{\text{in}}^{\text{O}_2, \text{Scrubbed}} &= \bar{y}_{\text{in}}^{\text{O}_2} \left(\frac{1}{1 - (\bar{y}_{\text{in}}^{\text{CO}} + \bar{y}_{\text{in}}^{\text{CO}_2} + \bar{y}_{\text{in}}^{\text{UHC}})} \right) \end{aligned}$$

$$X_{\text{out}}^{\text{O}_2, \text{Scrubbed}} = \frac{\bar{y}_{\text{out}}^{\text{O}_2, \text{Scrubbed}} \text{MW}_{\text{out}}}{\text{MW}_{\text{O}_2}}$$

$$X_{\text{in}}^{\text{O}_2, \text{Scrubbed}} = \frac{\bar{y}_{\text{in}}^{\text{O}_2, \text{Scrubbed}} \text{MW}_{\text{in}}}{\text{MW}_{\text{O}_2}}$$

Also, the volumetric flow rate of exhaust gas is equal to,

$$\dot{V} = \frac{\dot{m}_{\text{out}}}{\rho_{\text{out}}}$$

Therefore, Equation 3-4 becomes

$$\dot{Q}_{\text{comp}} = \left(X_{\text{in}}^{\text{O}_2, \text{Scrubbed}} - X_{\text{out}}^{\text{O}_2, \text{Scrubbed}} \right) \dot{m}_{\text{out}} \frac{\rho_{\text{O}_2}}{\rho_{\text{out}}} \Delta H_{\text{c,ox}} \quad (3-4b)$$

Equation 3-4b can be rewritten in terms of molecular weight ratio since the air and the oxygen are at the same conditions.

$$\frac{\rho_{\text{O}_2}}{\rho_{\text{out}}} = \frac{\left(\frac{P \text{MW}_{\text{O}_2}}{R_{\text{U}} T} \right)}{\left(\frac{P \text{MW}_{\text{out}}}{R_{\text{U}} T} \right)} = \frac{\text{MW}_{\text{O}_2}}{\text{MW}_{\text{out}}}$$

hence,

$$\dot{Q}_{\text{comp}} = \left(X_{\text{in}}^{\text{O}_2, \text{Scrubbed}} - X_{\text{out}}^{\text{O}_2, \text{Scrubbed}} \right) \dot{m}_{\text{out}} \frac{\text{MW}_{\text{O}_2}}{\text{MW}_{\text{out}}} \Delta H_{\text{c,ox}} \quad (3.4c)$$

$\Delta H_{\text{c,ox}}$ is defined as the heat of combustion per gram of oxygen consumed. Its value for propane is 12,800 kJ/kg. Because this value is based on complete combustion, which is not the case in study, Equation 3-4c must include a combustion efficiency factor, χ .

$$\dot{Q}_{\text{comp}} = \left(X_{\text{in}}^{\text{O}_2, \text{Scrubbed}} - X_{\text{out}}^{\text{O}_2, \text{Scrubbed}} \right) \dot{m}_{\text{out}} \frac{\text{MW}_{\text{O}_2}}{\text{MW}_{\text{out}}} \chi \Delta H_{\text{c,ox}} \quad (3-4d)$$

Chapter 3. A Parametric Study of the Effect of Fire Source Elevation on CO Levels Leaving a Compartment

To calculate the fuel mass flow rate based on the measured oxygen depletion, the heat release rate from Equation 3-4d is equated to the formula for the ideal heat release rate also accounting for incomplete combustion.

$$\dot{Q}_{\text{ideal}} = \dot{m}_{\text{fuel}, \text{O}_2 \text{ depleted}} \times (\chi \Delta H_c) = \dot{Q}_{\text{comp}}$$

So

$$\dot{m}_{\text{fuel}, \text{O}_2 \text{ depleted}} = \frac{\left(X_{\text{in}}^{\text{O}_2, \text{Scrubbed}} - X_{\text{out}}^{\text{O}_2, \text{Scrubbed}} \right) \dot{m}_{\text{out}} \frac{\text{MW}_{\text{O}_2}}{\text{MW}_{\text{out}}} \chi \Delta H_{c, \text{ox}}}{(\chi \Delta H_c)}$$

$$\dot{m}_{\text{fuel}, \text{O}_2 \text{ depleted}} = \frac{\left(X_{\text{in}}^{\text{O}_2, \text{Scrubbed}} - X_{\text{out}}^{\text{O}_2, \text{Scrubbed}} \right) \dot{m}_{\text{out}} \frac{\text{MW}_{\text{O}_2}}{\text{MW}_{\text{out}}} \Delta H_{c, \text{ox}}}{\Delta H_c} \quad (3-5)$$

The calculated fuel mass flow rate based on the measured oxygen depleted $\dot{m}_{\text{fuel}, \text{O}_2 \text{ depleted}}$ can be used as the denominator in Equation 2-23 and 2-24 to determine meaningful species yields. Indeed, the numerator and denominator of the new equations, Equation 3-6 and 3-7, are obtained from the same measurement technique.

$$Y^n = \frac{\dot{m}_{\text{out}}^n - \dot{m}_{\text{in}}^n}{\dot{m}_{\text{fuel}, \text{O}_2 \text{ depleted}}} \quad (3-6)$$

$$Y^{\text{O}_2} = \frac{\dot{m}_{\text{in}}^{\text{O}_2} - \dot{m}_{\text{out}}^{\text{O}_2}}{\dot{m}_{\text{fuel}, \text{O}_2 \text{ depleted}}} \quad (3-7)$$

Since it was determined by observation that all the fuel was burnt within the compartment, the ideal heat release rate and the heat release rate based on the measured depleted oxygen should be the same. Figure 3-6 shows that indeed the results are similar. The discrepancies can only be attributed to the method of measurement (Integration and averaging). The new methodology to obtain the species yields can then be applied.

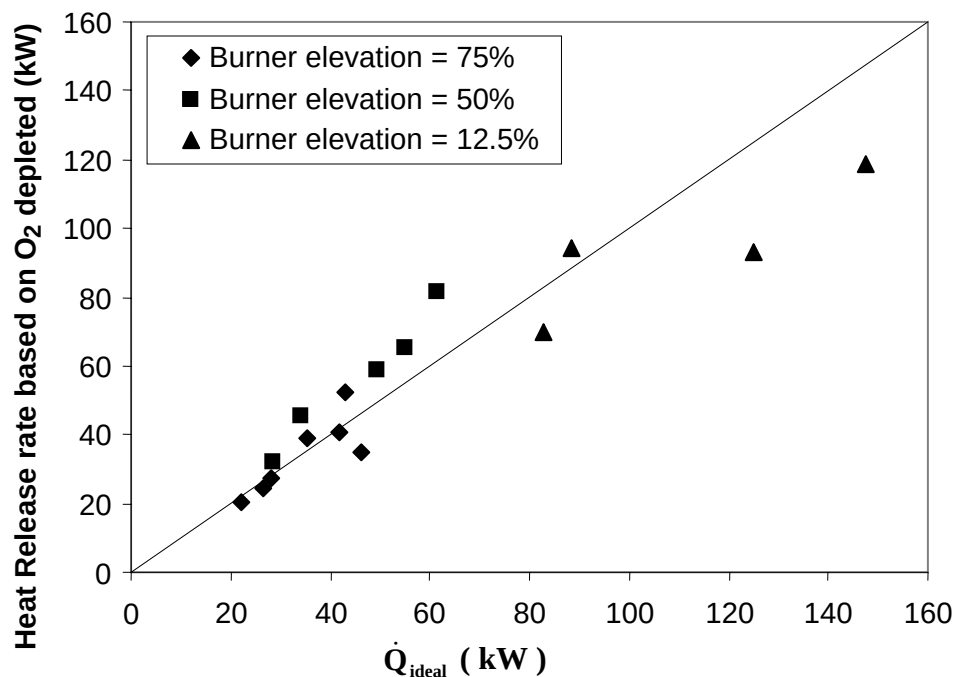


Figure 3-7: Heat Release Rate based on the measured oxygen depletion versus the Ideal Heat Release Rate

The results of the calculated species yields are presented in Figure 3-8 to Figure 3-10. These figures show respectively the carbon monoxide yield, the normalized carbon dioxide yield, and the normalized oxygen yield as a function of the ideal heat release rate.

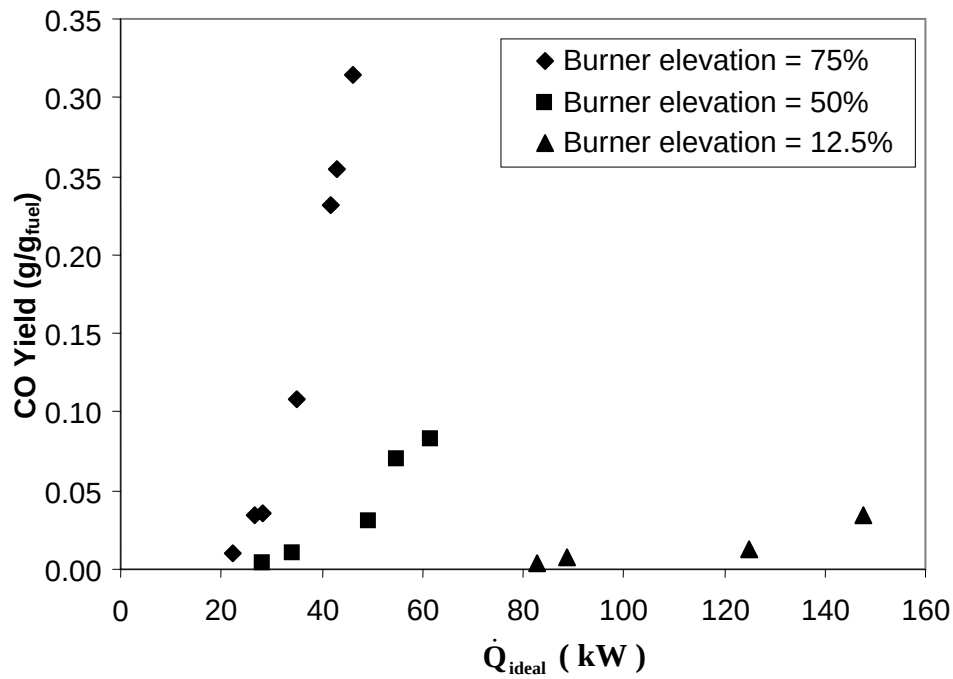


Figure 3-8: Carbon Monoxide species yield as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW).

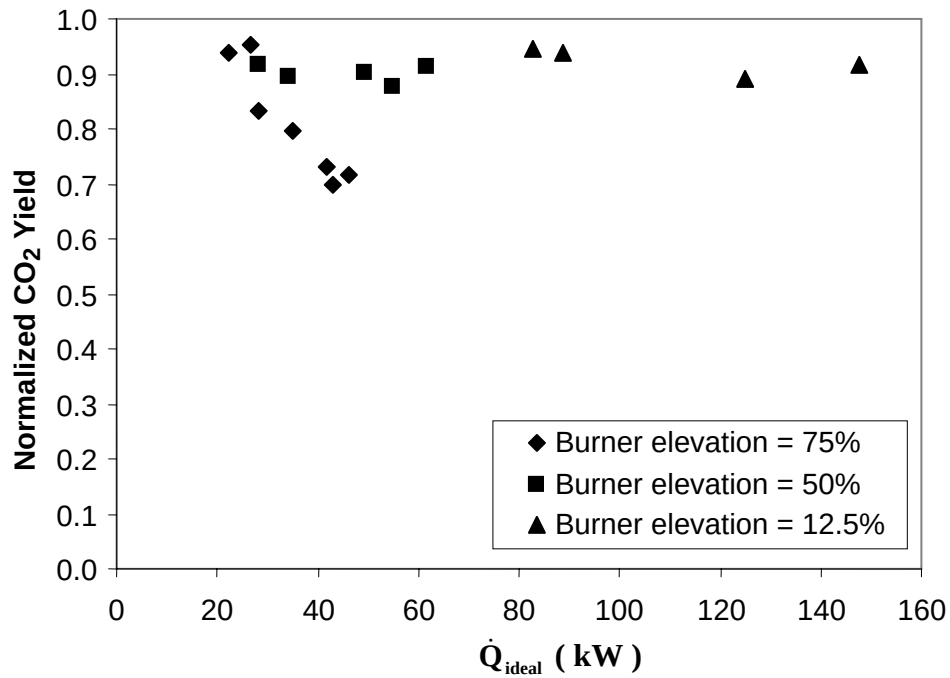


Figure 3-9: Normalized carbon dioxide species yield as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW).

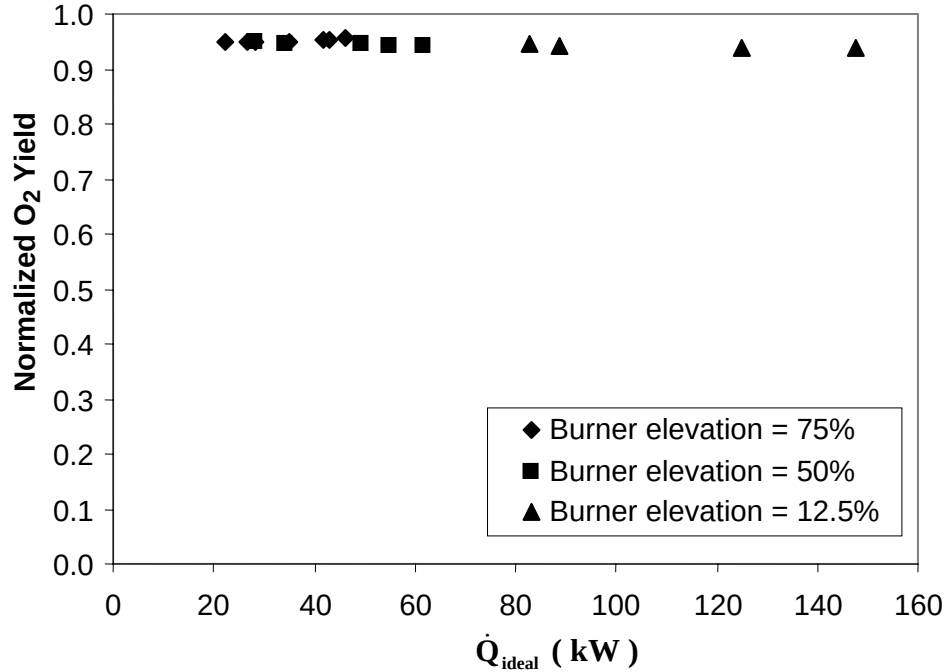


Figure 3-10: Normalized oxygen species yield as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW).

One curve for each burner elevation can be observed for the carbon monoxide and normalized carbon dioxide species yield. The effect of the burner elevation on the species production can be determined by analyzing these results.

From Figure 3-8, it can be seen that at equal ideal heat release rate, $\dot{Q}_{ideal}$ the carbon monoxide yields increased as the burner was elevated. The opposite can be observed in Figure 3-9 for the normalized carbon dioxide yields.

The difference in the slope of each curve indicates that the rate of change of the CO yields and normalized CO₂ yields with respect to $\dot{Q}_{ideal}$ was different for each burner elevation. At the highest elevation, the larger rate of increase for the carbon monoxide yield and the larger rate of decrease for the normalized carbon dioxide yield were observed. As the burner was lowered, the rates of change went down.

Chapter 3. A Parametric Study of the Effect of Fire Source Elevation on CO Levels Leaving a Compartment

In Figure 3-10, the normalized oxygen yield falls on the same line for all three burner elevations and was almost constant at a value of 0.94. The reason for this behavior is that the species yields were calculated based on the fuel mass flow rate burning inside the compartment obtained from the depleted oxygen.

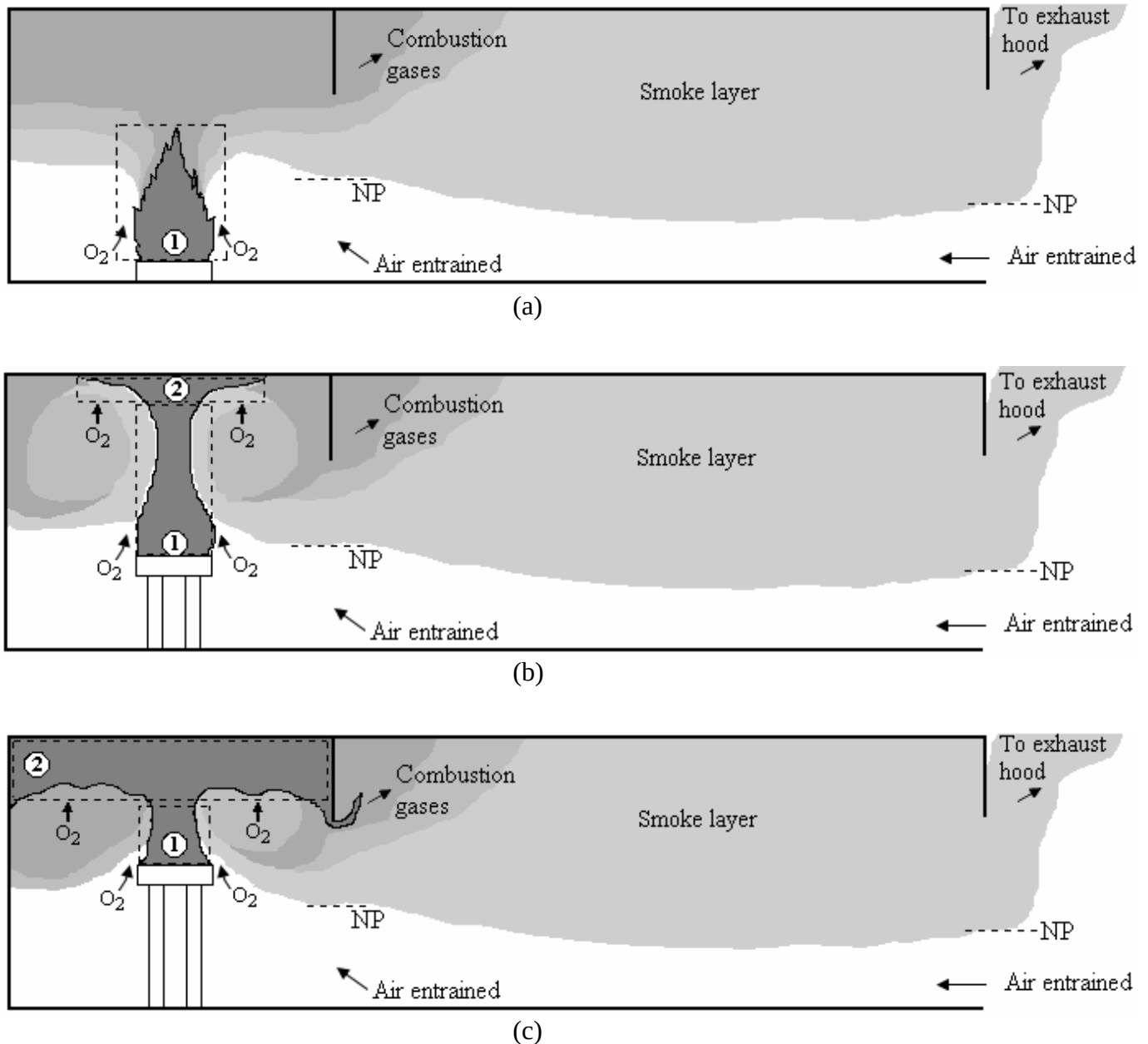


Figure 3-11: Schematic representation of the fire dynamic for three burner elevations at a fixed ideal heat release rate (47 kW), (a) $h/H_{Door} = 12.5\%$, (b) $h/H_{Door} = 50\%$ and (c) $h/H_{Door} = 75\%$.

Chapter 3. A Parametric Study of the Effect of Fire Source Elevation on CO Levels Leaving a Compartment

Figure 3-11, (a) (b) and (c) shows the schematic of the three burner elevation scenarios ($h/H_{\text{Door}} = 12.5\%$, $h/H_{\text{Door}} = 50\%$ and $h/H_{\text{Door}} = 75\%$ respectively) for a fixed $\dot{Q}_{\text{Ideal}}$. The ideal heat release rate of $\dot{Q}_{\text{Ideal}} = 47 \text{ kW}$ was chosen since observations revealed the presence of occasional flamelets at the top of the doorway for the burner elevation $h/H_{\text{Door}} = 75\%$.

For the burner elevation $h/H_{\text{Door}} = 12.5\%$ no complete test was performed for an ideal heat release rate of 47 kW because of the negligible levels of CO produced and the limited accuracy of the gas analyzer. However such a scenario was examined to draw an accurate schematic.

For each scenario, two zones have been defined to distinguish two reaction types. Zone 1 corresponds to the zone where the fuel burns at stoichiometric conditions using the oxygen from the air entrained through the doorway and directly into the fire plume. In zone 1 the reaction occurs as a flame sheet. The fuel remaining unburned is transported within the fire plume into the upper layer. Zone 2 represents the section of the upper layer where the unburned fuel reacts. The combustion within zone 2 is made possible due to the presence of oxygen entrained from the air into the upper layer. The composition of the upper layer gas being non homogeneous and oxygen deficient, zone 2 behaves as a poorly-mixed and fuel-rich reactor in which the combustion is incomplete.

In Figure 3-11 (a), with the burner at the 12.5% elevation, all of the fuel burns in zone 1. Since enough oxygen is available from the surrounding air only products of complete combustion are produced.

In Figure 3-11 (b), the burner being closer to the upper layer, at the 50% elevation, the oxygen from the entrained air is not sufficient for all the fuel to react in zone 1. A small portion of the fuel burns in zone 2 resulting in the production of low level of carbon monoxide.

In Figure 3-11 (c), the fire source is raised into the upper layer at the 75 % elevation. A limited amount of air can be entrained along the fire plume allowing most of the fuel to burn in zone 2. Very high carbon monoxide levels are being generated in this configuration. When the lower limit of zone 2 is near the top of the doorway, occasional wisps of flame were observed for an ideal heat release rate of 47 kW.

3.2.5 Species Yields versus the Global Equivalence Ratio

The customary methodology of presenting the species yields as a function of the global equivalence ratio ϕ was applied to the data. The results are shown in Figure 3-12 to Figure 3-14. It can be seen that the methodology fails to correlate the data. Indeed, as explained by Wieczorek [2003] the assumption that the global equivalence ratio is equal to the plume equivalence ratio cannot be made in the case of a compartment with prototypical building features since more complex mixing occurs within the compartment between the two contiguous gas layers. Moreover, the fire was over ventilated in all tests performed.

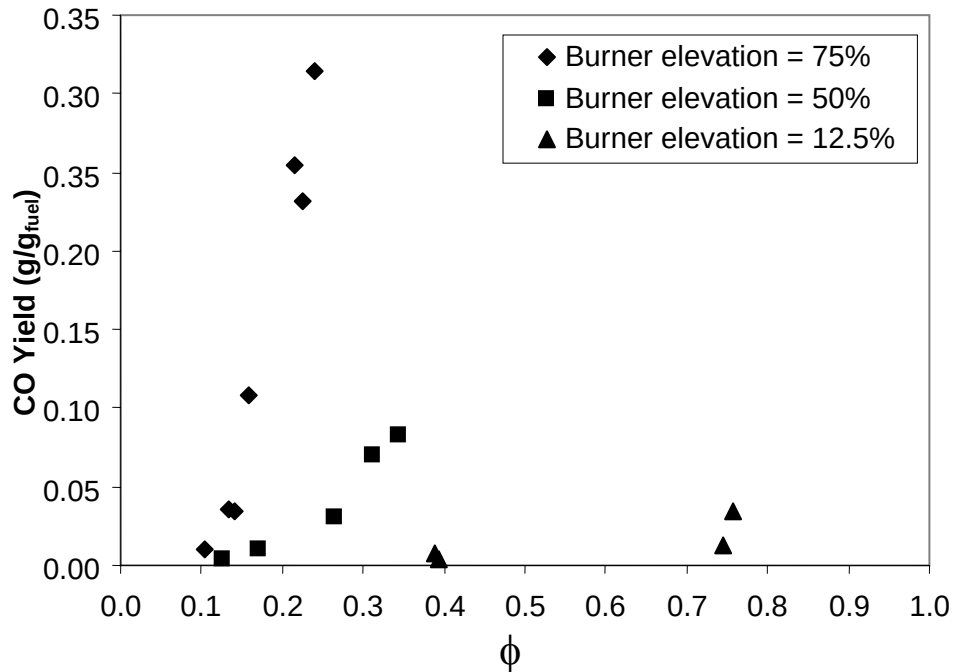


Figure 3-12: Carbon monoxide species yield as a function of the global equivalence ratio ϕ .

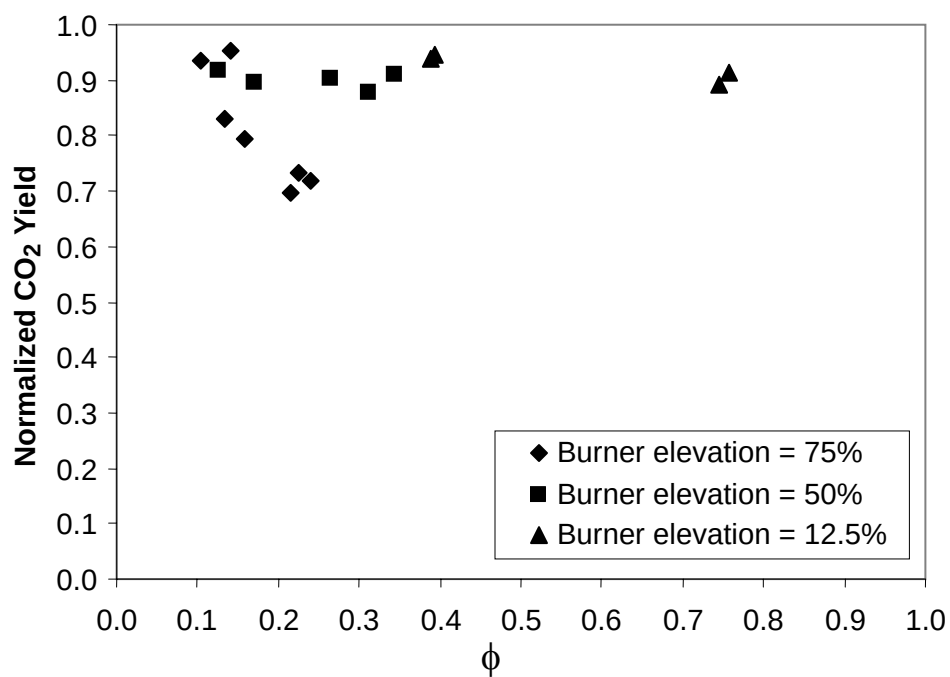


Figure 3-13: Normalized carbon dioxide species yield as a function of the global equivalence ratio ϕ .

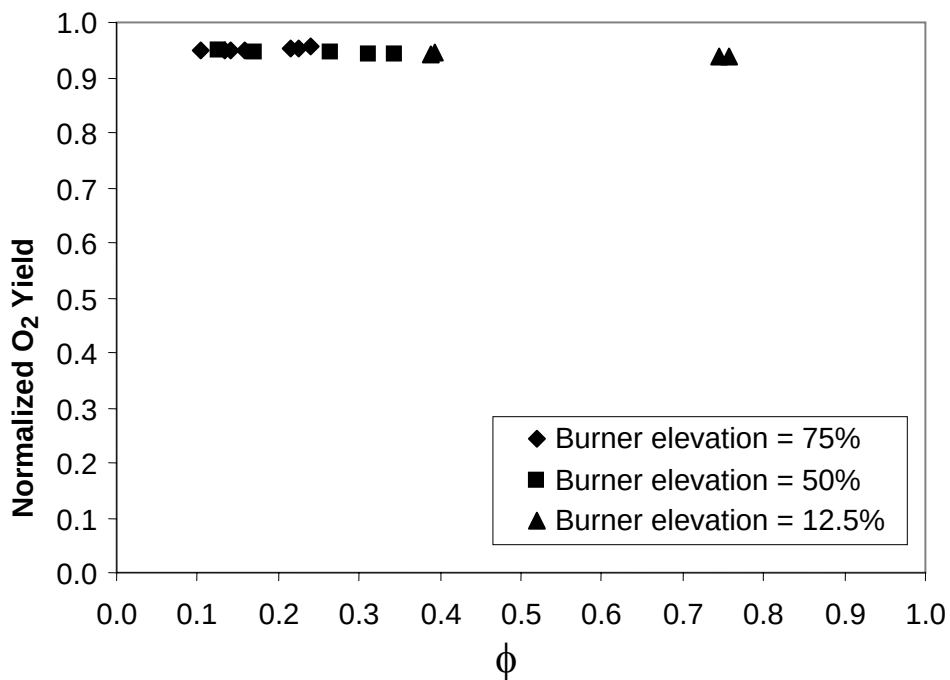


Figure 3-14: Normalized oxygen species yield as a function of the global equivalence ratio ϕ .

3.2.6 Species Yields versus the Non Dimensional Heat Release Rate

In order to calculate the non dimensional heat release rate defined by Wieczorek [2003], the heat release rate required for the flame to reach the top of the doorway had to be determined.

To do so, systematic observations of the compartment doorway top, through the side glass window, were performed for each test. External flaming was only observed for the burner elevation $h/H_{\text{Door}} = 75\%$.

For the burner elevations $h/H_{\text{Door}} = 12.5\%$ and $h/H_{\text{Door}} = 50\%$ flame extensions were not observed. Instead, a limit for these configurations was reached attributed the hallway and the ventilation conditions studied. The smoke layer along the hallway reached the floor and observation of the top of the doorway through the side glass window only revealed hot glowing soot. Figure 3-15 shows pictures taken through the side glass window of external burning (a) and hot glowing soot (b).

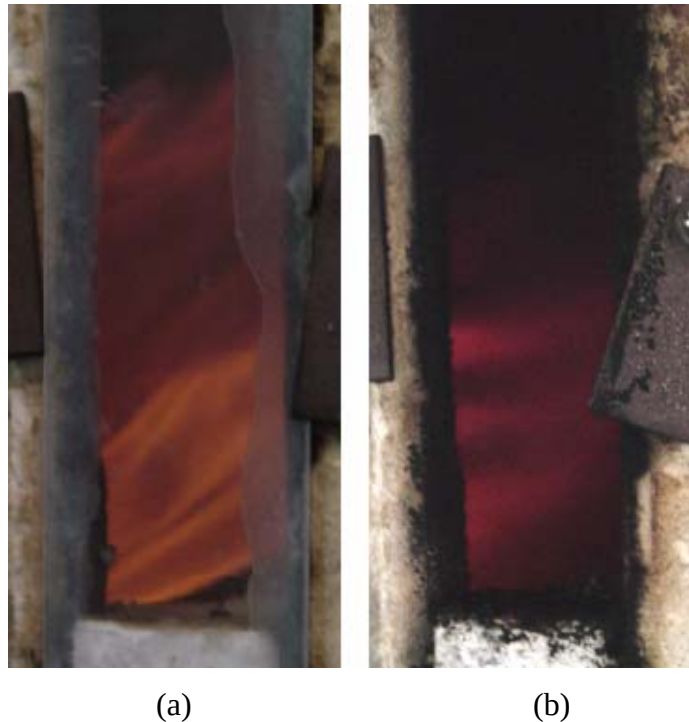


Figure 3-15: Pictures of the limit cases through the glass side window. (a) Flame extension for the burner elevation $h/H_{\text{Door}} = 75\%$, (b) Hot soot glowing for the burner elevation $h/H_{\text{Door}} = 50\%$.

Chapter 3. A Parametric Study of the Effect of Fire Source Elevation on CO Levels Leaving a Compartment

When the smoke layer reached the floor of the hallway, the simple two layer flow along the hallway ceased to exist. A more complex flow dynamic took place and the measurements of gas composition and gas velocity at the compartment doorway were not steady anymore leading to meaningless results.

Because of the absence of flame extensions for $h/H_{Door}=12.5\%$ and $h/H_{Door}=50\%$, A new definition was given to the non dimensional heat release rate, Equation 3-8.

$$\hat{Q} = \frac{\dot{Q}_{ideal}}{\dot{Q}_{MaxCO}} \quad (3-8)$$

The non dimensional heat release rate $\hat{Q}$ is the ratio of the ideal heat release rate $\dot{Q}_{ideal}$ divided by the heat release rate at which the maximum level of CO were observed, $\dot{Q}_{MaxCO}$. Table 3-4 contains the values of $\dot{Q}_{MaxCO}$ obtained for each burner elevation.

Table 3-4: $\dot{Q}_{MaxConfig}$ observed for each burner elevations.

Burner Elevation	$\dot{Q}_{MaxCO}$ (kW)
12.5 %	147
50 %	61
75 %	46

Schematic drawing of each configuration at various ideal heat release rates are shown in Figure 3-16, Figure 3-17 and Figure 3-18 for the burner elevation $h/H_{Door}=12.5\%$, $h/H_{Door}=50\%$ and $h/H_{Door}=75\%$ respectively.

In Figure 3-16, the burner was on the floor, $h/H_{Door}=12.5\%$. Figure 3-16 (a) shows the fire dynamic for an ideal heat release rate lower than the ideal heat release rate corresponding to the maximum CO levels ($\dot{Q}_{ideal} < \dot{Q}_{MaxCO}$ so $\hat{Q} < 1$). The smoke layer thickness is not preventing the air to flow inside the compartment and the fuel burns mostly below the upper layer. Small quantities of carbon monoxide are generated in this case.

Chapter 3. A Parametric Study of the Effect of Fire Source Elevation on CO Levels Leaving a Compartment

In Figure 3-16 (b), the fuel mostly burns within the upper layer where the amount of oxygen is limited and the combustion results in the higher production of carbon monoxide ($\dot{Q}_{\text{ideal}} = \dot{Q}_{\text{MaxCO}}$ so $\hat{Q} = 1$).

When the ideal heat release rate is further increased, the phenomenon depicted in Figure 3-16 (c) takes place. The smoke layer reaches the floor of the hallway. Indeed, the hallway doorway is not wide enough. The combustion products production rate is larger than the evacuated rate through the hallway doorway. Once this state is reached, the measurements at the compartment doorway of gas composition and gas velocity are not steady anymore. This results in a moving neutral plane since its location is obtained from velocity measurements. Moreover, the data reduction process is based on the assumption that a quasi steady state is reached. The measurements being so unsteady, the species yields calculated from them are meaningless.

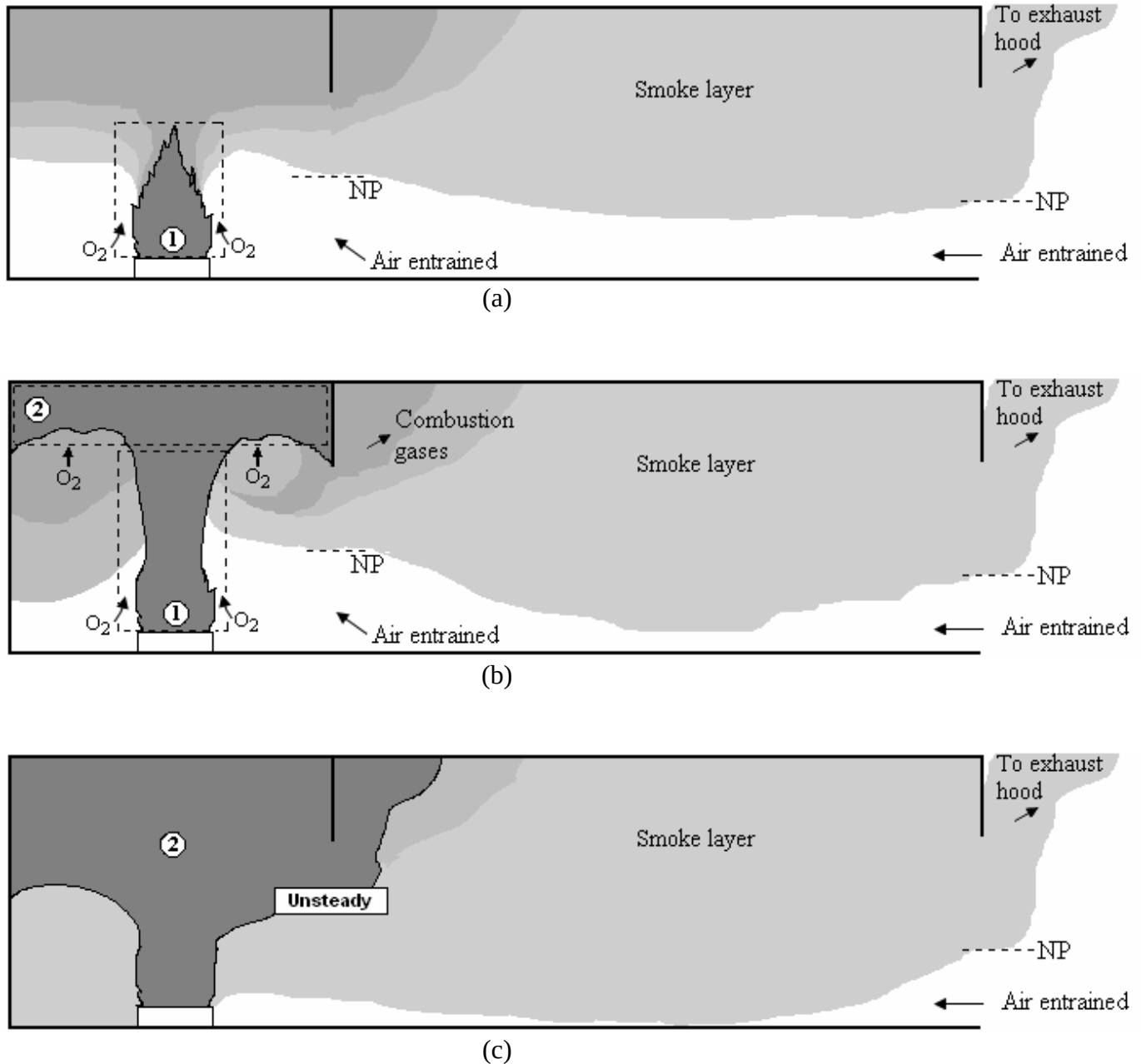


Figure 3-16: Schematic representation of the fire scenario for different values of ideal heat release rates for the burner elevation $h/H_{Door} = 12.5\%$. (a) $\hat{Q} < 1$, (b) $\hat{Q} = 1$ and (c) $\hat{Q} > 1$.

In Figure 3-17, the burner is located at the burner elevation $h/H_{Door} = 50\%$. The scenario depicted is similar to the one for the burner on the floor ($h/H_{Door} = 12.5\%$). However, the ideal heat release rate resulting in the smoke layer reaching the hallway floor is smaller.

Chapter 3. A Parametric Study of the Effect of Fire Source Elevation on CO Levels Leaving a Compartment

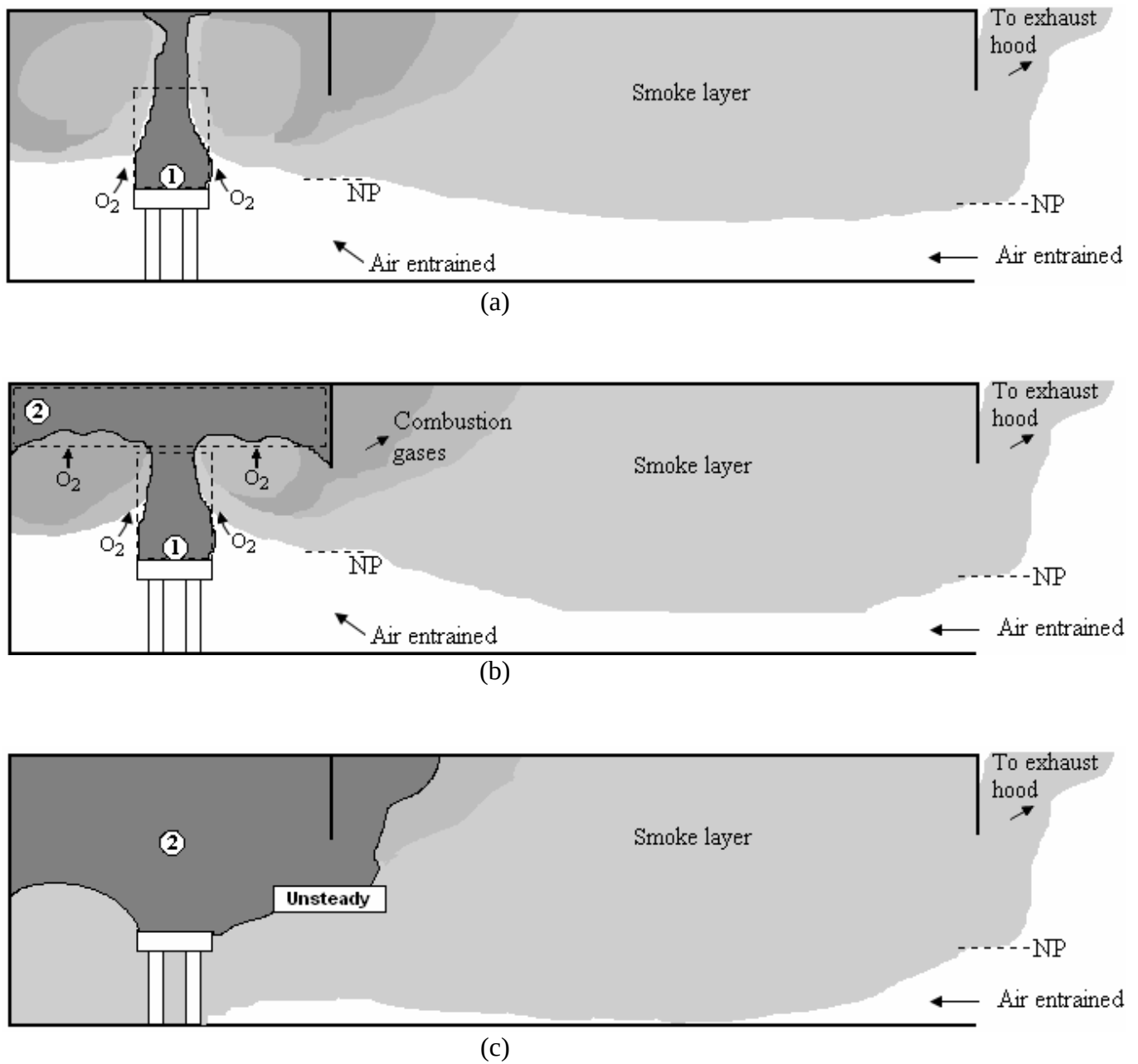


**Figure 3-17: Schematic representation of the fire scenario for different values of ideal heat release rates for the burner elevation $h/H_{Door} = 50\%$.
(a) $\hat{Q} < 1$, (b) $\hat{Q} = 1$ and (c) $\hat{Q} > 1$.**

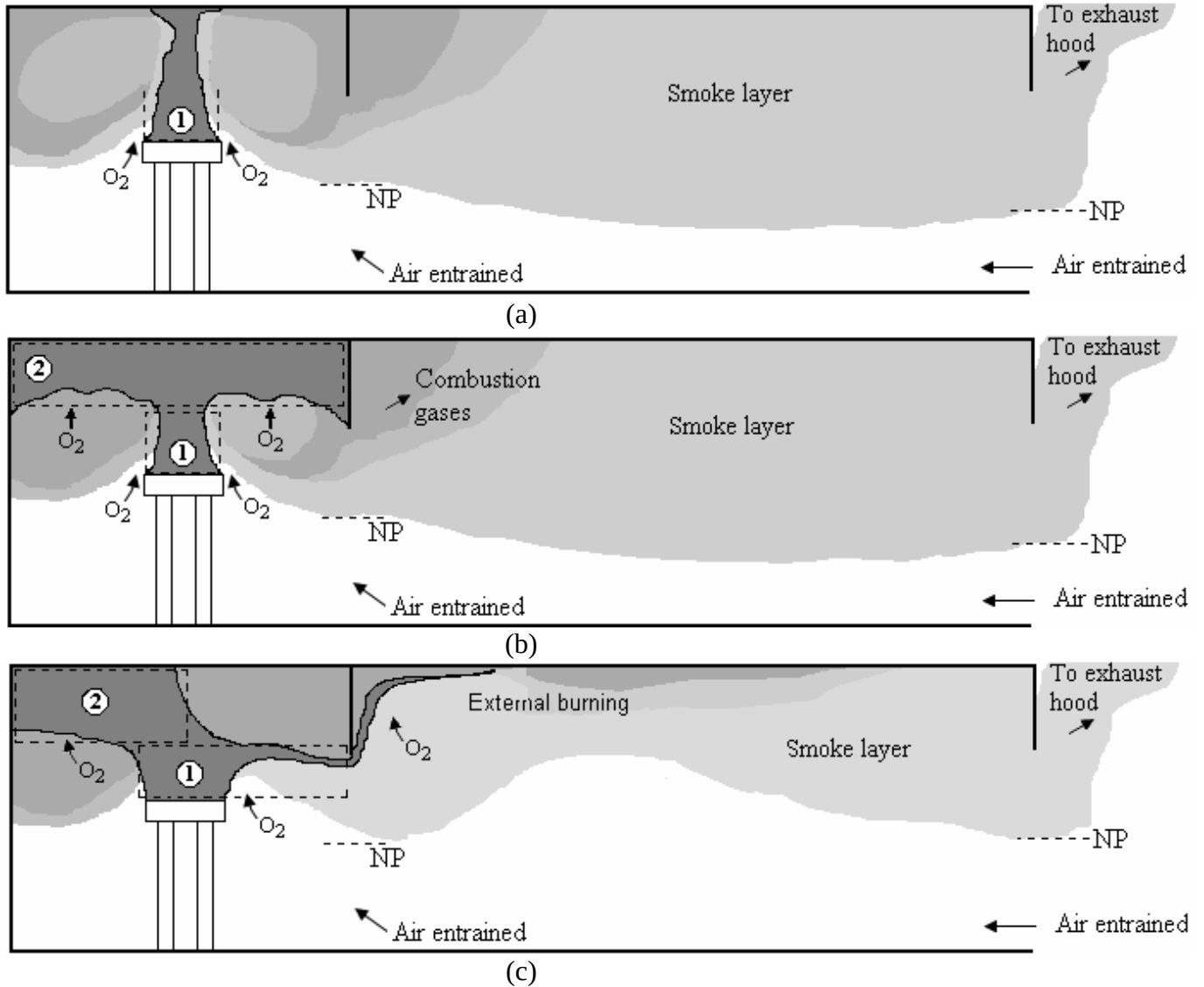


**Figure 3-18: Schematic representation of the fire scenario for different values of ideal heat release rates for the burner elevation $h/H_{Door} = 75\%$.
(a) $\hat{Q} < 1$, (b) $\hat{Q} = 1$, (c) $\hat{Q} > 1$**

Figure 3-18 shows a different scenario that only was observed for the burner elevation at $h/H_{Door}=75\%$. In Figure 3-18 (a) for $\hat{Q} < 1$, the levels of CO are low but they are increasing as the ideal heat release rate is increased to $\dot{Q}_{ideal} = \dot{Q}_{MaxCO}$ where tiny wisps of flames are observed at the top of the doorway; Figure 3-18 (b) ($\hat{Q} = 1$). For higher ideal heat release rates constant external flaming appears at the top of the doorway and decreasing levels of CO are measured; Figure 3-18 (c).

Chapter 3. A Parametric Study of the Effect of Fire Source Elevation on CO Levels Leaving a Compartment

The calculated species yields along with the redefined non dimensional heat release rate $\hat{Q}$ are listed in Table 3-4 for all cases reported in this section.

The species yields as a function of the non dimensional heat release rate $\hat{Q}$ are shown in Figure 3-19 through Figure 3-21.

Table 3-5: Species yields and calculated $\hat{Q}$.

Test Number	Burner Elevation	$\hat{Q}$	CO Yield (g/g _{fuel})	Normalized CO ₂ Yield	Normalized O ₂ Yield
0303210	12.50%	0.56	0.004	0.95	0.94
0211220	12.50%	0.60	0.007	0.94	0.94
0303211	12.50%	0.85	0.013	0.89	0.94
0303212	12.50%	1.00	0.035	0.91	0.94
0303213*	12.50%	1.09	0.032	0.93	0.94
0409110	50%	0.47	0.004	0.92	0.95
0409130	50%	0.56	0.010	0.89	0.95
0409131	50%	0.81	0.031	0.90	0.95
0409132	50%	0.90	0.070	0.88	0.94
0311181	50%	1.00	0.083	0.91	0.94
0409111*	50%	1.12	0.006	0.92	0.94
0408250	75%	0.48	0.011	0.94	0.95
0406090	75%	0.58	0.034	0.95	0.95
0408251	75%	0.61	0.036	0.83	0.95
0408252	75%	0.77	0.108	0.79	0.95
0408253	75%	0.91	0.231	0.73	0.95
0408310	75%	0.94	0.254	0.70	0.95
0406220	75%	1.00	0.315	0.72	0.96
0408311*	75%	1.13	0.305	0.78	0.95

* Not reported in this chapter

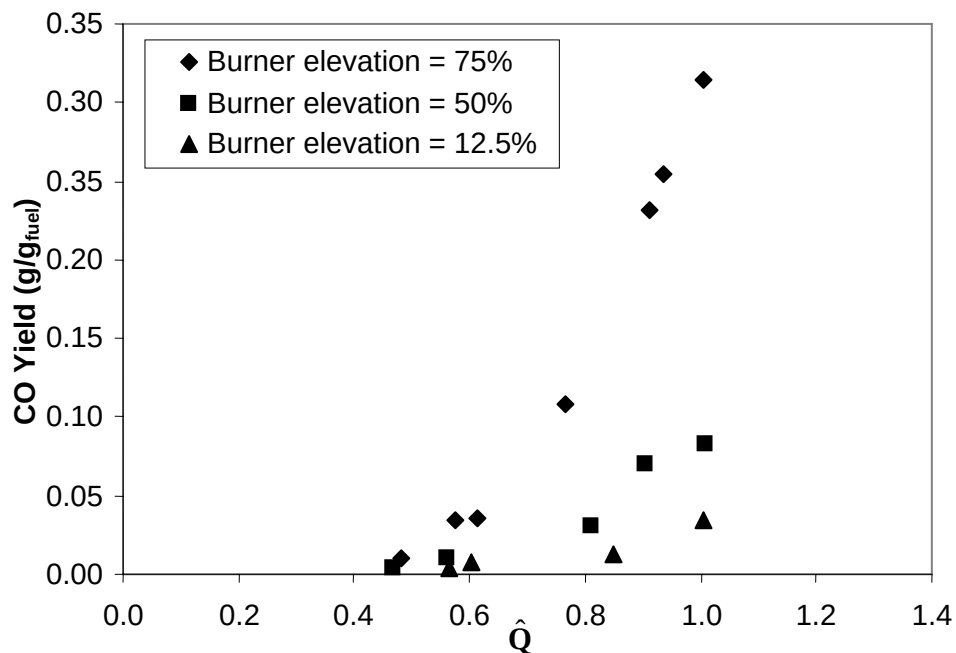


Figure 3-19: Carbon Monoxide species yield as a function of the non dimensional heat release rate $\hat{Q}$.

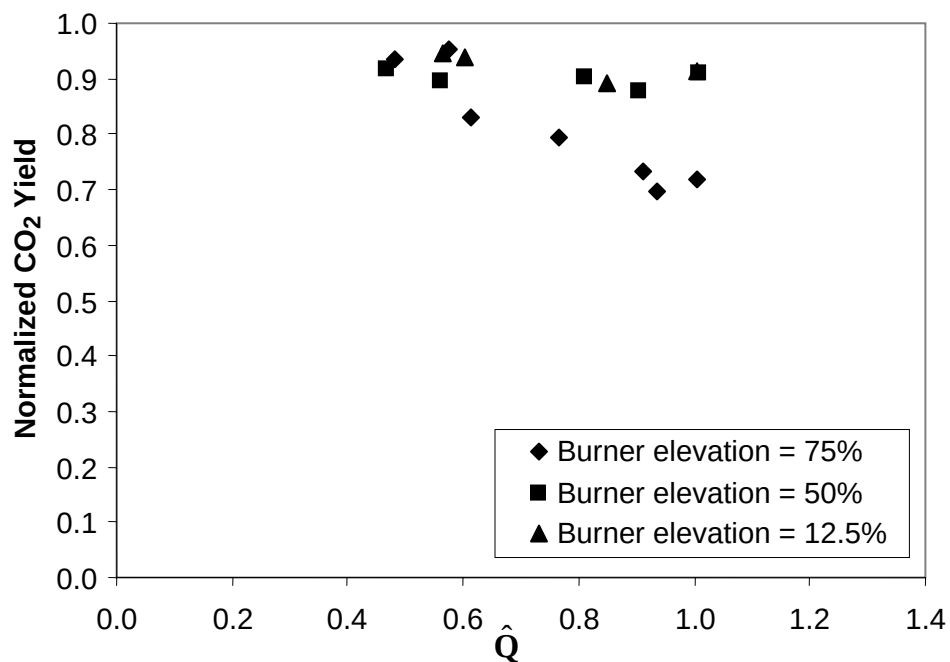


Figure 3-20: Normalized carbon dioxide species yield as a function of the non dimensional heat release rate $\hat{Q}$.

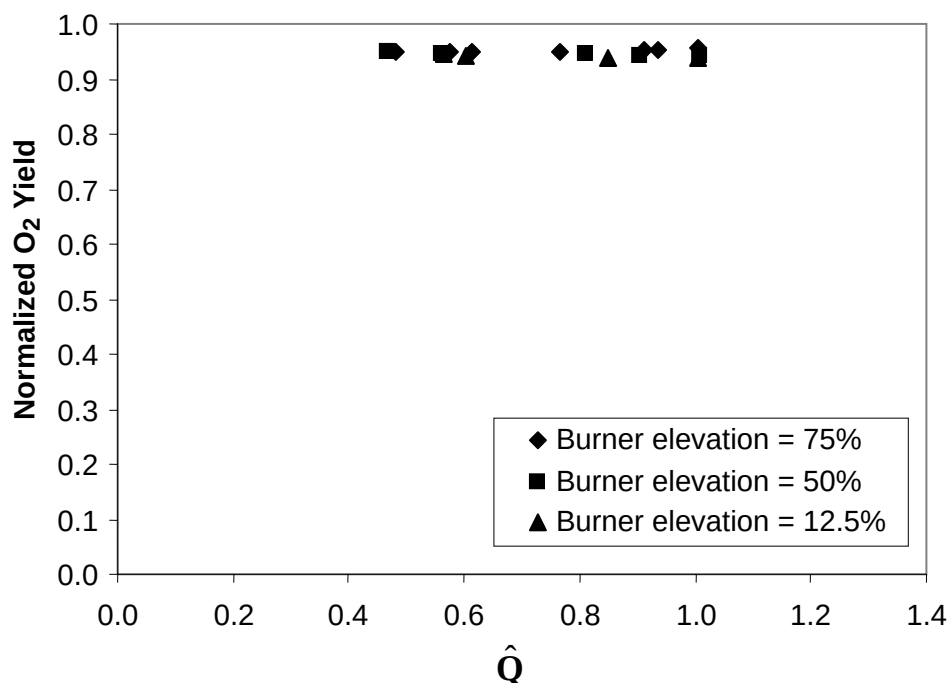


Figure 3-21: Normalized oxygen species yield as a function of the non dimensional heat release rate $\hat{Q}$.

When presenting the data in this manner three different curves are observed, one for each burner elevation. However, using the carbon monoxide yield normalized with respect to the maximum **measured** CO yield for each configuration as the dependant variable collapses the data onto a single curve. The data is presented in Figure 3-22. The maximum measured CO yields for each configuration are shown in Table 3-6.

Table 3-6: Maximum CO yield for each burner elevation configuration at $\hat{Q}=1$

Burner Elevation	$Y_{Max Config}^{CO}$
12.5 %	0.035
50 %	0.083
75 %	0.308

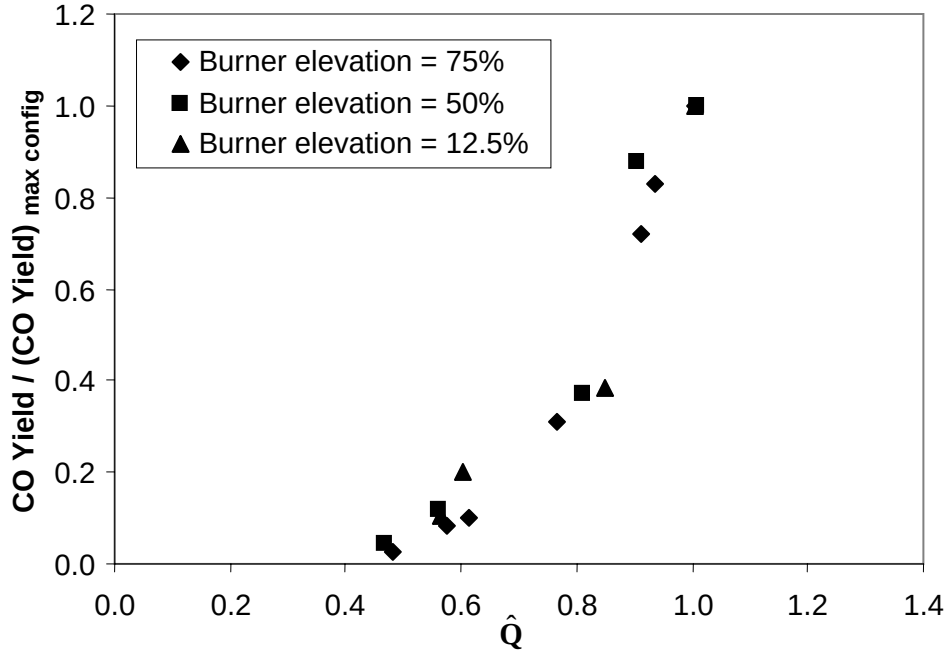


Figure 3-22: Normalized carbon monoxide species yield as a function of the non dimensional heat release rate $\hat{Q}$.

3.3 CORRELATION DEVELOPMENT

Correlations for the data presented in the previous section are developed based on a regression analysis for the normalized carbon monoxide yield as a function of the non-dimensional heat release rate, $\hat{Q}$. Similar to the method used by Wieczorek [2003] to obtain correlations, the program CurveExpert (version 1.34) was used. The method to develop the correlation is based on non-linear regression. A Sigmoidal or "S-shaped" growth curve was used to represent the data over the range of $\hat{Q}$ examined.

Equation 3-9 predicts the normalized CO yields as a function of the non dimensional heat release rate over the range $0.48 < \hat{Q} < 1$.

$$\frac{Y^{\text{CO}}}{Y_{\text{Max Config}}^{\text{CO}}} = \frac{a \cdot b + c \cdot \hat{Q}^d}{b + \hat{Q}^d} \quad (3-9)$$

The values for the coefficients a, b, c, and d are

With:

a = 0.097006654
b = 0.28082834
c = 1.2504999
d = 11.22299

The standard error for the curve was 0.072 and the R^2 value was 0.985.

The curve fit to the data is presented in Figure 3-23. To verify the correlation, Equation 3-9 was used for each configuration and the results of the carbon monoxide yield as a function of the non dimensional heat release rate are presented in Figure 3-24.

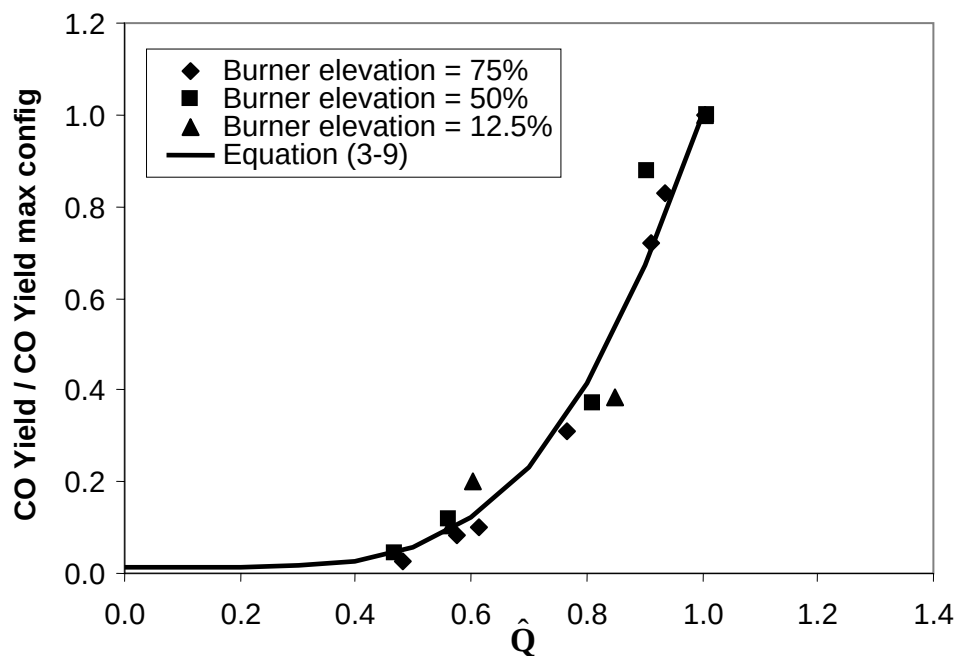


Figure 3-23: Non dimensional carbon monoxide species yield as a function of the non dimensional heat release rate $\hat{Q}$ along with a curve fit to the data.

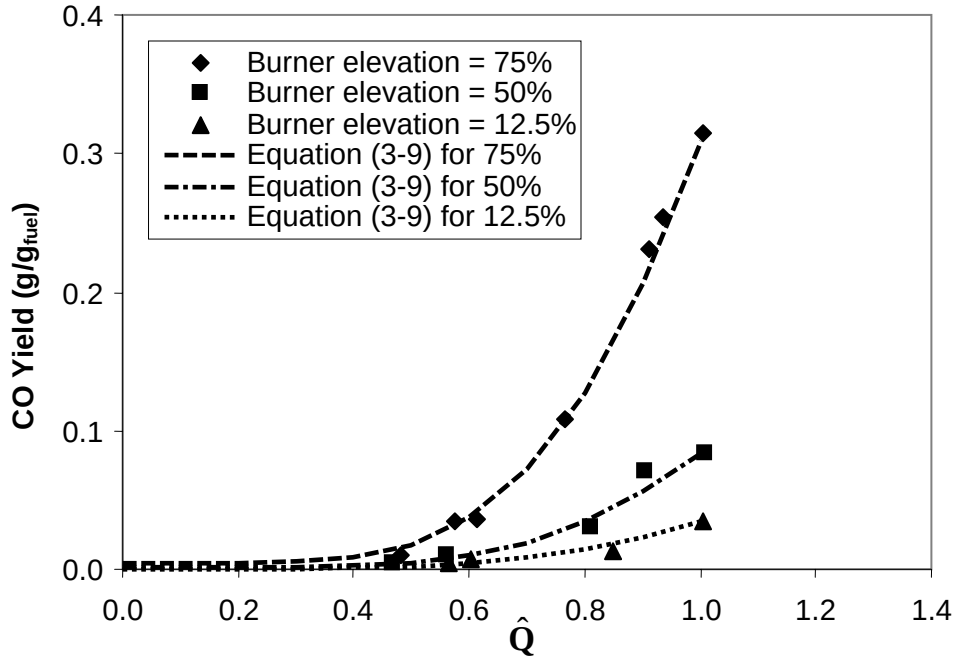


Figure 3-24: Carbon monoxide species yield as a function of the non dimensional heat release rate $\hat{Q}$ along with a curve fit to the data.

From the conservation of carbon atoms applied to the compartment an equation for the normalized CO_2 yields was obtained based on the correlation obtained for the carbon monoxide yields. The assumption that all the fuel was burnt inside the compartment and that no soot was formed. All carbon atoms from the fuel were oxidized to either CO or CO_2 .

$$f_{\text{CO}_2} = 1 - f_{\text{CO}}$$

Where the normalized carbon monoxide yield f_{CO} and the normalized carbon dioxide yield f_{CO_2} are:

$$f_{\text{CO}} = \frac{Y^{\text{CO}}}{Y_{\text{theory}}^{\text{CO}}} = \frac{Y^{\text{CO}}}{1.91} \quad \text{and} \quad f_{\text{CO}_2} = \frac{Y^{\text{CO}_2}}{Y_{\text{theory}}^{\text{CO}_2}} = \frac{Y^{\text{CO}_2}}{3.00}$$

With the theoretical maximum yields:

$$Y_{\text{theory}}^{\text{CO}_2} = 3(\text{g/g}_{\text{fuel}}) \quad \text{and} \quad Y_{\text{theory}}^{\text{CO}} = 1.91(\text{g/g}_{\text{fuel}})$$

The theoretical maximum yields are the mass of a species produced or consumed by stoichiometric combustion of one mole of fuel.

So,

$$f_{\text{CO}_2} = 1 - \frac{Y^{\text{CO}}}{1.91}$$

And using the correlation for Y^{CO} from equation (3-9),

$$f_{\text{CO}_2} = 1 - \frac{\frac{a \cdot b + c \cdot \hat{Q}^d}{b + \hat{Q}^d} Y_{\text{Max Config}}^{\text{CO}}}{1.91} \quad (3-10)$$

The normalized carbon dioxide yields are presented in Figure 3-25 along with the correlation obtained, Equation 3-10, applied to each burner elevation. Although consistently lower due to the omission of soot in the calculations, the data behave the same way as the prediction curves. Since no measurements were made on the soot generation, these results cannot be verified.

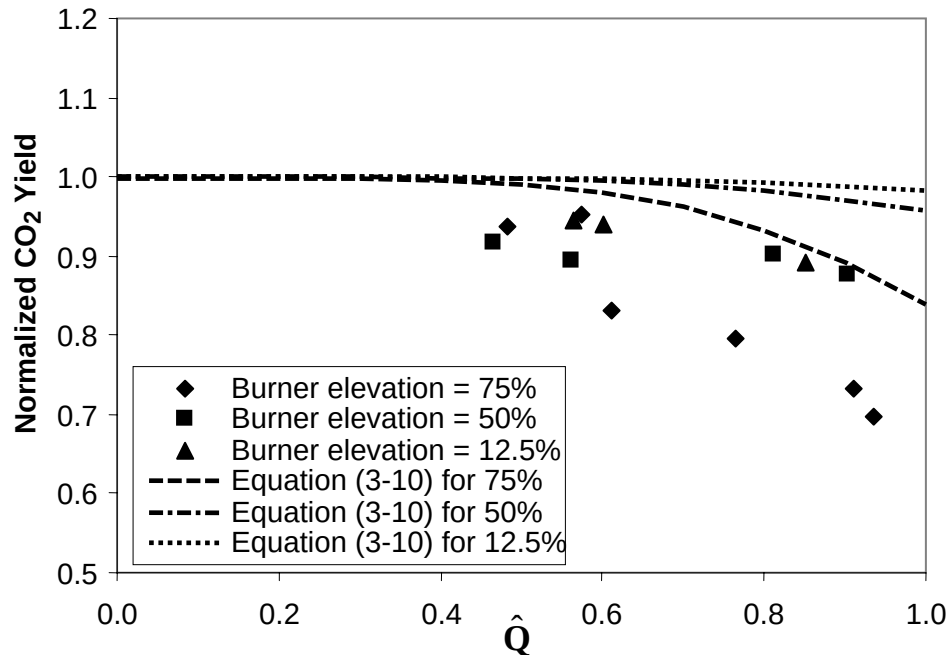


Figure 3-25: Normalized carbon dioxide species yield as a function of the non-dimensional heat release rate $\hat{Q}$ along with the correlation obtained for the normalized CO₂ yield applied to each configuration.

CHAPTER 4 – CARBON MONOXIDE TRANSPORT STUDY

4.1 MOTIVATION FOR TRANSPORT STUDY

The transport of carbon monoxide generated by an enclosure fire to a confined adjacent space has been investigated by Ewens [1994], Lattimer [1996] and Wieczorek [2003]. All reported a dependency of the CO levels transported on the fluid dynamic inside the hallway, the oxygen availability, and the temperature of the exhaust gases. When external burning was observed, some of the CO generated inside the compartment was oxidized to CO₂, lowering the toxicity of the transported exhaust gases.

Wieczorek [2003] conducted a transport study for fires contained within the compartment using the same experimental set up used in the present research. The effects of the ventilation size located at the exit of the 6.1m long hallway on the air entrainment rates and the species transport were examined. For the over ventilated fires investigated, the addition of the hallway did not perceptibly impact the species production. When the compartment doorway and the ideal heat release rate were kept constant, the hallway doorway width effects on the air entrainment rates were studied. The reduction of the doorway width at the hallway exit plane allowed Wiecezorek [2003] to observe a decrease in the air entrainment mass flow rate into the compartment.

However, when both doorway sizes were kept constant and the ideal heat release rate was varied, the air entrainment into the compartment remained constant.

For the simple geometric configuration examined in previous works, valuable observations were made on the impacts of the ventilation conditions, fire dynamics and flow dynamics onto the species production and transport. In real fires, such as the Hillhaven nursing home tragedy in 1989, the geometry is much more complex. However, a complete understanding of the basic geometric parameters controlling the CO production and transport in simple configurations could allow predictions to be made for more realistic scenarios.

In addition to the work performed by Wieczorek [2003], the present study investigated the effects of the hallway and the burner elevation on the air entrainment and the carbon monoxide transport.

4.2 PRESENTATION OF THE RESULTS

4.2.1 Transport Study Test Matrix

The transport study was conducted for all three burner elevations with fixed ventilation conditions. A baseline doorway was installed at the compartment exit plane ($x=0$ m), and a narrow doorway at the hallway exit plane ($x=6.1$ m). The tests discussed in the previous chapter all included measurements at the hallway exit doorway. The results from these measurements are analyzed in this chapter and compared to the data obtained at the compartment exit plane.

Table 4-1: Transport study test matrix

Test Number	Burner Elevation	Fuel Mass Flow Rate (kg/s)	Fire Size (kW)
0303210	12.50%	1.79E-03	83
0211220	12.50%	1.91E-03	89
0303211	12.50%	2.70E-03	125
0303212	12.50%	3.19E-03	148
0409150*	12.50%	3.47E-03	160
0409110	50%	6.14E-04	28
0409130	50%	7.41E-04	34
0409131	50%	1.07E-03	49
0409132	50%	1.19E-03	55
0311181	50%	1.33E-03	61
0409111*	50%	1.47E-03	68
0408250	75%	4.79E-04	22
0406090	75%	5.72E-04	26
0408251	75%	6.08E-04	28
0408252	75%	7.61E-04	35
0408253	75%	9.05E-04	41
0408310	75%	9.30E-04	43
0406220	75%	9.97E-04	46
0408311**	75%	1.12E-03	52
0406221**	75%	1.20E-03	55
0310100**	75%	1.25E-03	58
0408312**	75%	1.34E-03	62

* Results not reported due to unsteadiness of the measurements

** Presence of external burning

To study the effects of the external burning on the species produced and their transport, additional cases were investigated for the burner elevation $h/H_{\text{Door}}=75\%$. As explained in the previous chapter, no external burning was observed for the other two burner elevations. Table 4-1 contains the test matrix for the transport study.

The results from the two tests referred as 0409150 and 0409111 are not reported. The continuously changing flow dynamics at the compartment doorway for both cases did not provide a steady state period. The smoke layer reached the floor of the hallway and very unsteady values of local species mass fractions and local velocities were observed leading to inconsistent results.

4.2.2 Carbon Monoxide Yields versus the Ideal Heat Release Rate at Both Locations

The carbon monoxide yields at both locations as a function of the ideal heat release rate are shown in Figure 4-1, Figure 4-2 and Figure 4-3 for each burner elevation ($h/H_{\text{Door}}=12.5\%$, $h/H_{\text{Door}}=50\%$ and $h/H_{\text{Door}}=75\%$ respectively).

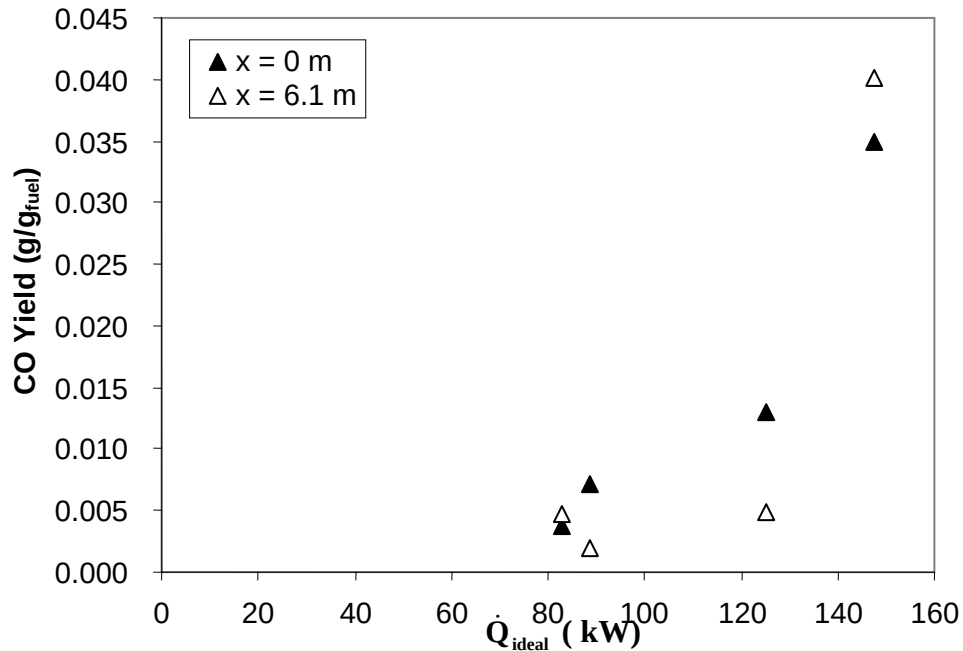


Figure 4-1: Carbon Monoxide species yield (based on the fuel burning inside the compartment) at the compartment doorway ($x = 0$ m) and at the hallway doorway ($x = 6.1$ m) as a function of the ideal heat release rate $\dot{Q}_{\text{ideal}}$ (kW) for $h/H_{\text{Door}}=12.5\%$.

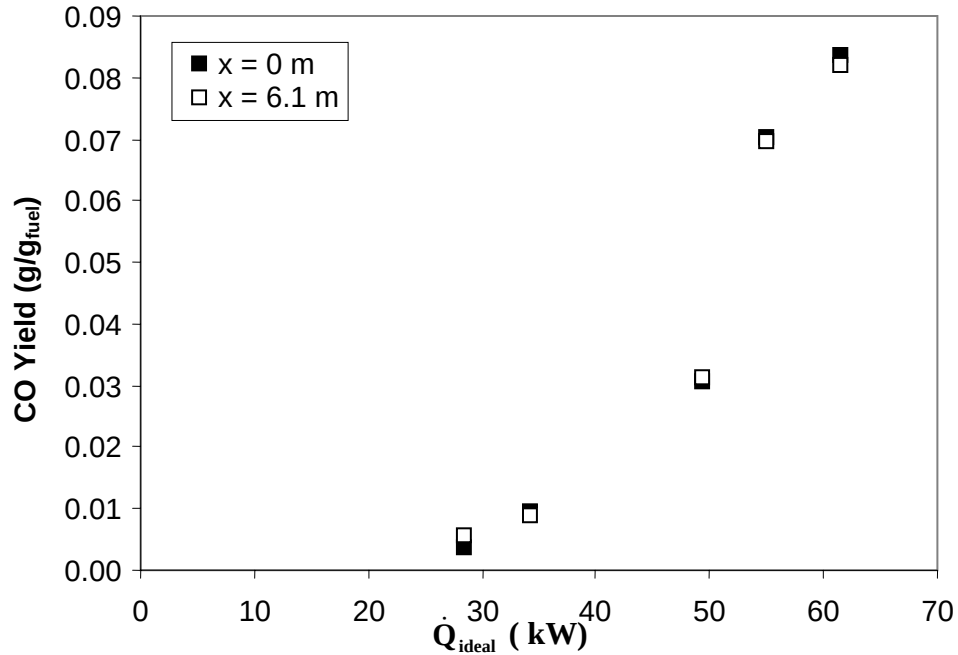


Figure 4-2: Carbon Monoxide species yield (based on the fuel burning inside the compartment) at the compartment doorway ($x = 0$ m) and at the hallway doorway ($x = 6.1$ m) as a function of the ideal heat release rate $\dot{Q}_{ideal}$ (kW) for the 50 % burner elevation.

For the burner elevations $h/H_{Door} = 12.5\%$ and $h/H_{Door} = 50\%$ the values of the carbon monoxide yields at the compartment doorway, $x=0$ m, and at the hallway doorway, $x= 6.1$ m, are very similar. Since no external burning was present for each of the cases represented in Figure 4-1 and Figure 4-2, the oxidation reaction of CO to CO₂ was frozen. The carbon monoxide levels generated inside the compartment were therefore transported along the hallway. This comparison between the locations $x=0$ m and $x=6.1$ m was made possible since no external burning was observed. The combustion was contained within the compartment implying that the carbon monoxide yields measured at the compartment doorway were based on the same amount of fuel as the carbon monoxide yields measured at the hallway doorway.

When the burner elevation was $h/H_{\text{Door}} = 75\%$, external burning was present for ideal heat release rates higher than 47 kW. In this case, the carbon monoxide yields could not be compared between the locations $x=0$ m and $x=6.1$ m since they were based on a different amount of fuel. To be able to compare the results and draw conclusions on the carbon monoxide transport, the yields at both locations were calculated based on the total amount of fuel burning in the system consisting of the compartment and the hallway.

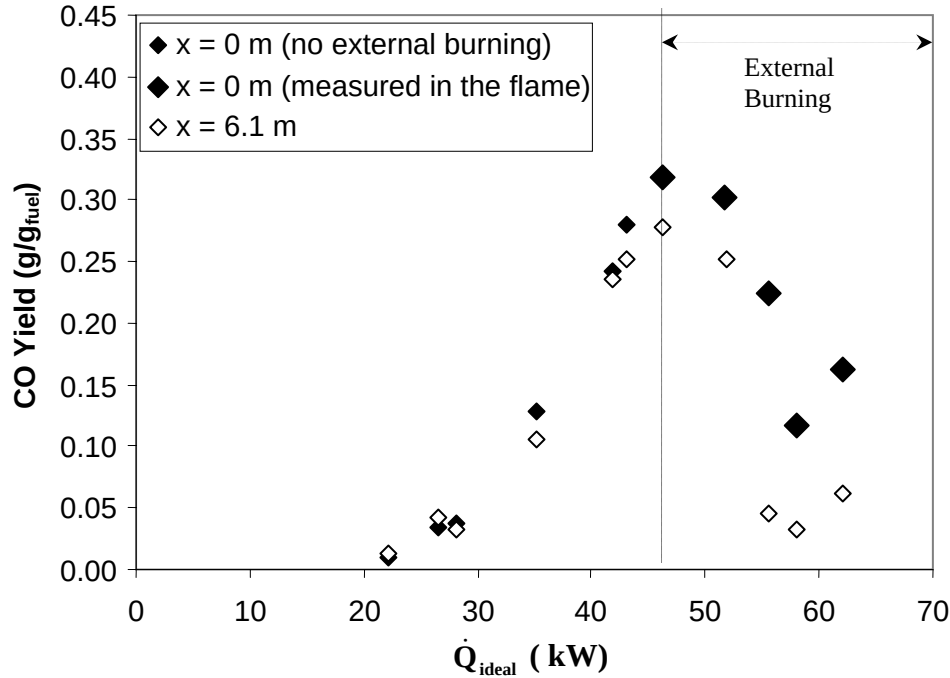


Figure 4-3: Carbon Monoxide species yield (based on the total amount of fuel) at the compartment doorway ($x = 0$ m) and at the hallway doorway ($x = 6.1$ m) as a function of the ideal heat release rate $\dot{Q}_{\text{ideal}}$ (kW) for the 75 % burner elevation.

In Figure 4-3 for the burner elevation $h/H_{\text{Door}} = 75\%$ at ideal heat release rates below 47 kW, when the fire is contained inside the compartment, the values of the carbon monoxide yields at the compartment doorway, $x=0$ m, and at the hallway doorway, $x=6.1$ m, are very similar. However, for the last four tests performed at higher $\dot{Q}_{\text{ideal}}$, a different trend is observed. At this elevation, sustained external burning was present. The levels of carbon monoxide measured at the compartment exit plane are decreasing for increasing $\dot{Q}_{\text{ideal}}$. Moreover, the levels of carbon monoxide measured at $x=6.1$ m are

consistently lower than the one measured at $x=0$ m. This indicates the occurrence of carbon monoxide oxidation to carbon dioxide. The oxidation reaction is attributed to the external burning. Indeed, the presence of flames outside the compartment implies oxygen availability and temperatures higher than 850 K.

In an attempt to explain the transition occurring once external burning was sustained, schematics of the system were drawn based on visual observations.

The scenario represented in Figure 4-4 was discussed in section 3.2.3. It is the scenario for which tiny irregular wisps of flames were observed. The insufficient amount of air entrained along the fire plume limited the zone where the combustion was complete (zone 1). Most of the fuel was allowed to burn in zone 2 where the oxygen deficiency turned the upper layer into a poorly-mixed fuel rich reactor. This scenario, for the burner elevation $h/H_{\text{Door}} = 75\%$, happened at a value of $\dot{Q}_{\text{ideal}} = 47$ kW and corresponded to the highest carbon monoxide levels generated within the compartment.

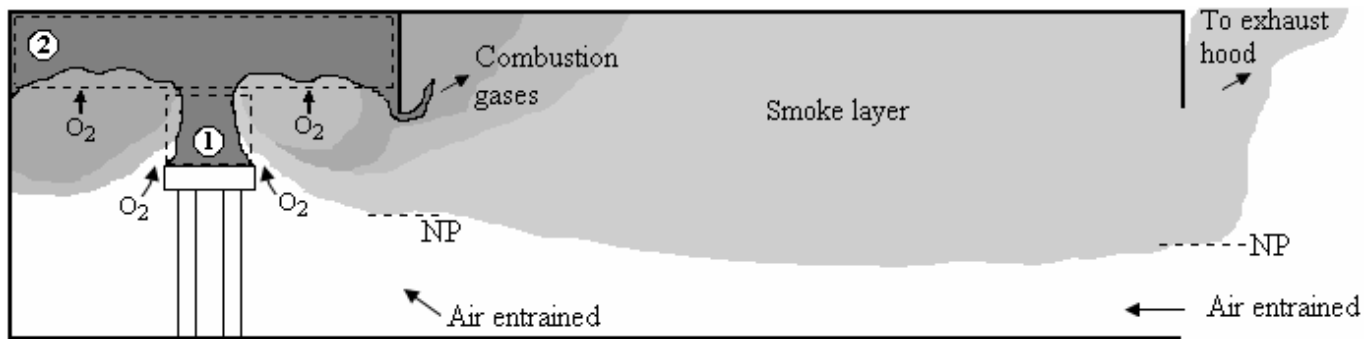


Figure 4-4: Schematic of a scenario for $h/H_{\text{Door}} = 75\%$ prior to external burning.

Sustained flaming appeared for a slightly higher ideal heat release rate, impinging on the hallway ceiling and creating ceiling jet flames; Figure 4-5.

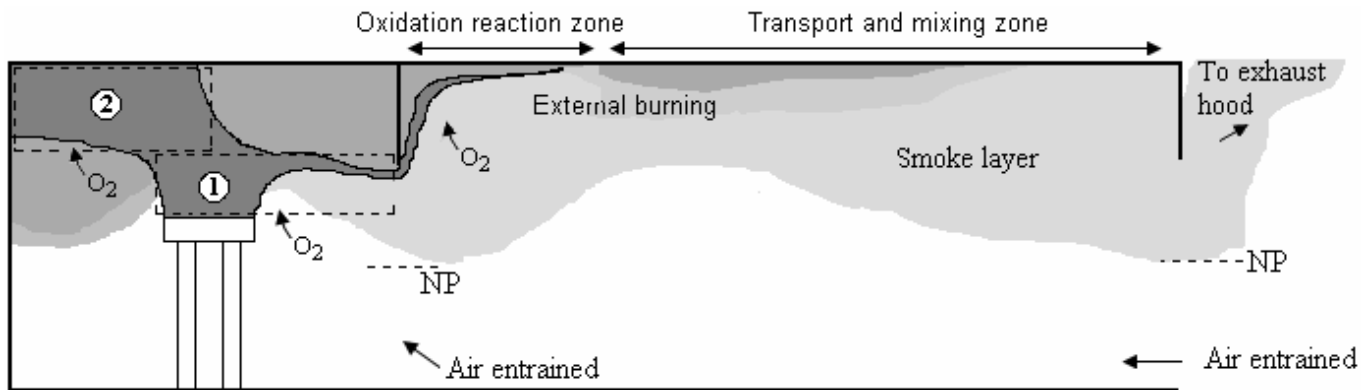


Figure 4-5: Schematic of a scenario for $h/H_{Door} = 75\%$ with sustained external burning.

For this scenario, lower levels of carbon monoxide were generated inside the compartment. It was explained in the previous chapter that for external burning to be sustained and visible in the form of diffusion flame sheets, fuel and oxygen had to be provided constantly from both sides of the flame. The decrease in carbon monoxide levels observed once external burning was sustained was attributed to the tendency of the fire dynamic to tend to the scenario shown in Figure 4-6. A small amount of fuel is burning inside the compartment to sustain and keep the flame attached to the burner. Since this fuel burns where oxygen is provided by the air entrained directly through the doorway, the combustion of the fuel burning inside the compartment is almost complete and carbon monoxide levels generated inside the compartment tend to 0. The unburned hydrocarbon burning externally as flame extensions are also being provided sufficient oxygen from the air of the cold layer. The reaction directly outside the compartment is then complete and results in the formation of CO_2 and none or very little CO.

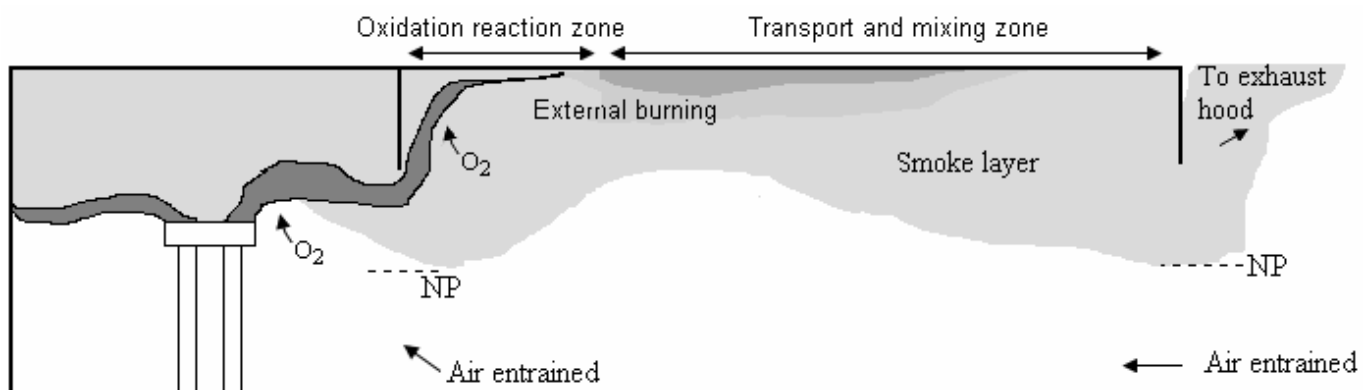


Figure 4-6: Schematic of a scenario for $h/H_{Door} = 75\%$ with minimum fuel burning within the compartment.

When sustained external burning was observed, only occurring for the burner elevation $h/H_{\text{Door}} = 75\%$, the combustion process within the system was more efficient and resulted in less incomplete combustion (i.e., less smoke). The smoke layer depth decreased and the flame was visible from the hallway doorway; Figure 4-7.



Figure 4-7: Picture of the sustained external burning with the burner at $h/H_{\text{Door}} = 75\%$ and an ideal heat release rate of 52 kW

4.3 HALLWAY VENTILATION SIZE EFFECTS ON THE FLOW DYNAMIC

It was shown in the previous Chapter that a combustion reaction occurring within an oxygen vitiated environment results in a higher carbon monoxide production. The smoke accumulating inside the hallway due to an insufficient rate of evacuation would contribute to an increase in the upper layer thickness inside the compartment, thus increasing the amount of fuel burning incompletely. The smoke evacuation (i.e., combustion products) and the air entrainment into the system (compartment + hallway) occurred through the hallway ventilation. The effects of the hallway ventilation size on the flow dynamic were therefore analyzed.

4.3.1 Hallway Ventilation Size Effects on the Air Entrainment

The air entrainment mass flow rate into the compartment was discussed in Section 3.2.2. Figure 4-8 shows the air mass flow rate entrained into the compartment as a function of the ideal heat release rate for the tests listed in Table 4-1. For all cases, even when external burning was observed, the fire was over ventilated ($\phi < 1$).

The theoretical maximum air mass flow rates through the doorways, referred as ventilation limits, were calculated in the previous Chapter; Table 3-3.

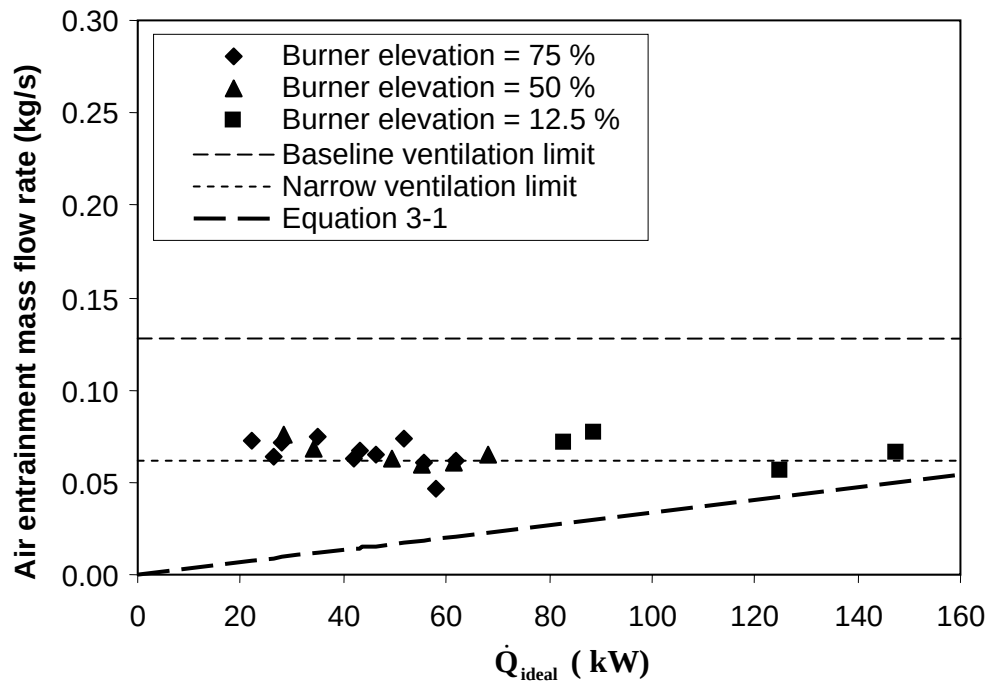


Figure 4-8: Air entrainment mass flow rate through the compartment doorway as a function of the ideal heat release rate $\dot{Q}_{ideal}$.

For all cases, the air entrainment mass flow rate into the compartment was significantly higher than the mass flow rate of air required for the fuel to burn at stoichiometric conditions (obtained from Equation 3-1). The observed values were much lower than the calculated ventilation limit $\dot{m}_{air}^{ventlimit}$ of the baseline doorway installed at this location. Indeed, when the hallway end doorway is smaller than the compartment doorway, the air entrainment mass flow rate into the compartment is expected to be controlled by the hallway end doorway. This is supported by the data which shows the air

entrainment mass flow rate into the compartment equal to the calculated ventilation limit $\dot{m}_{\text{air}}^{\text{ventlimit}}$ of the narrow doorway installed at the hallway end.

No dependency of the air entrainment mass flow rates to either the ideal heat release rate or the burner elevation was observed. However, the values for all tests fell around the calculated ventilation limit $\dot{m}_{\text{air}}^{\text{ventlimit}}$ of the narrow doorway located at $x=6.1\text{m}$.

The air entrainment mass flow rates measured through the narrow doorway installed at the hallway exit plane are shown in Figure 4-9.

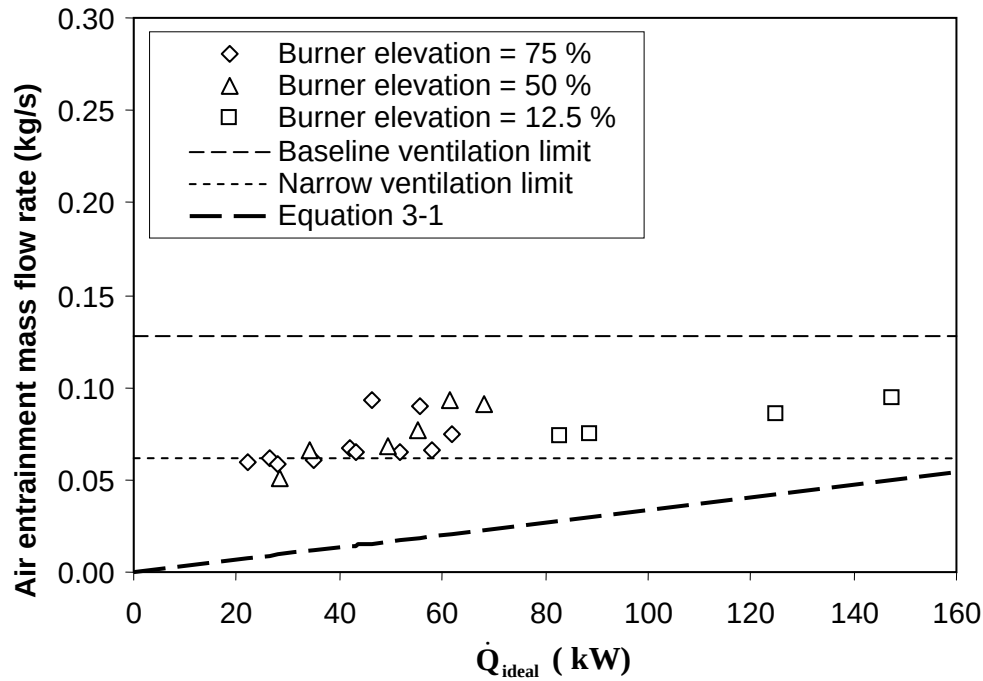


Figure 4-9: Air entrainment mass flow rate through the hallway doorway as a function of the ideal heat release rate $\dot{Q}_{\text{ideal}}$.

From Figure 4-9, it can be seen that the air entrainment into the system was not affected by the burner elevation. However, as the ideal heat release rate was increased, the air entrainment mass flow rate increased slowly to values above the calculated ventilation limit of the narrow doorway installed at this location.

4.3.2 Hallway Ventilation Size Effects on the Carbon Monoxide Transport

For each experiment, local species mole fractions were measured at all points of the sampling grid for both doorways. A color coded contour mapping of the species mole fraction for each species was plotted in order to visualize the gas composition and the species spatial distribution. The case shown in Figure 4-10 and Figure 4-11 corresponds to an ideal heat release rate of 52 kW and a burner elevation $h/H_{Door}=75\%$ at the compartment doorway and the hallway doorway respectively. It should be noted that for the O_2 mole fraction mapping, the color code was reversed emphasizing on the location where the concentration was smaller.

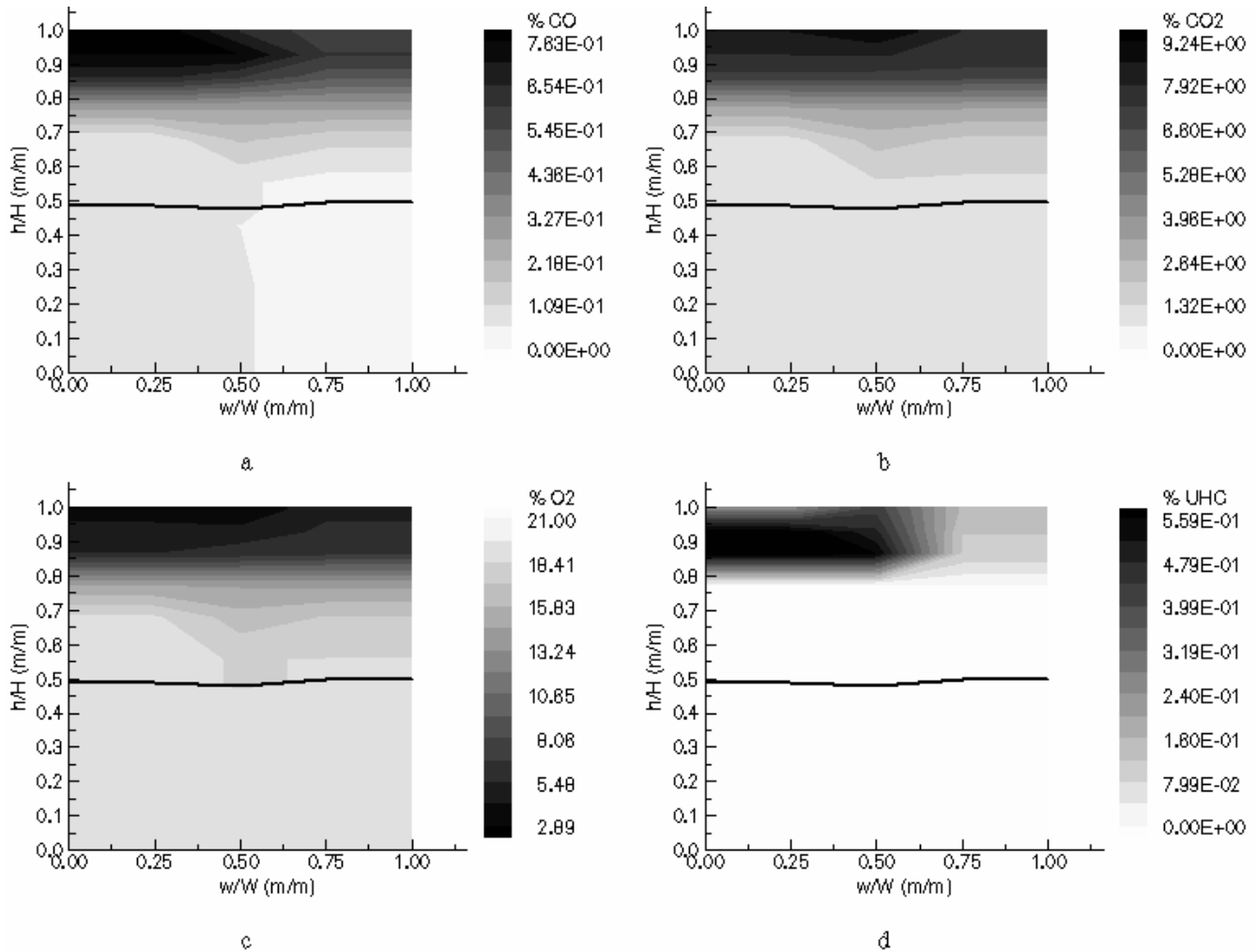


Figure 4-10: Compartment doorway species mole fractions mapping for a heat release rate of 62kW and a burner elevation $h/H_{Door} = 75\%$. (a) CO, (b) CO₂, (c) O₂ and (d) UHC

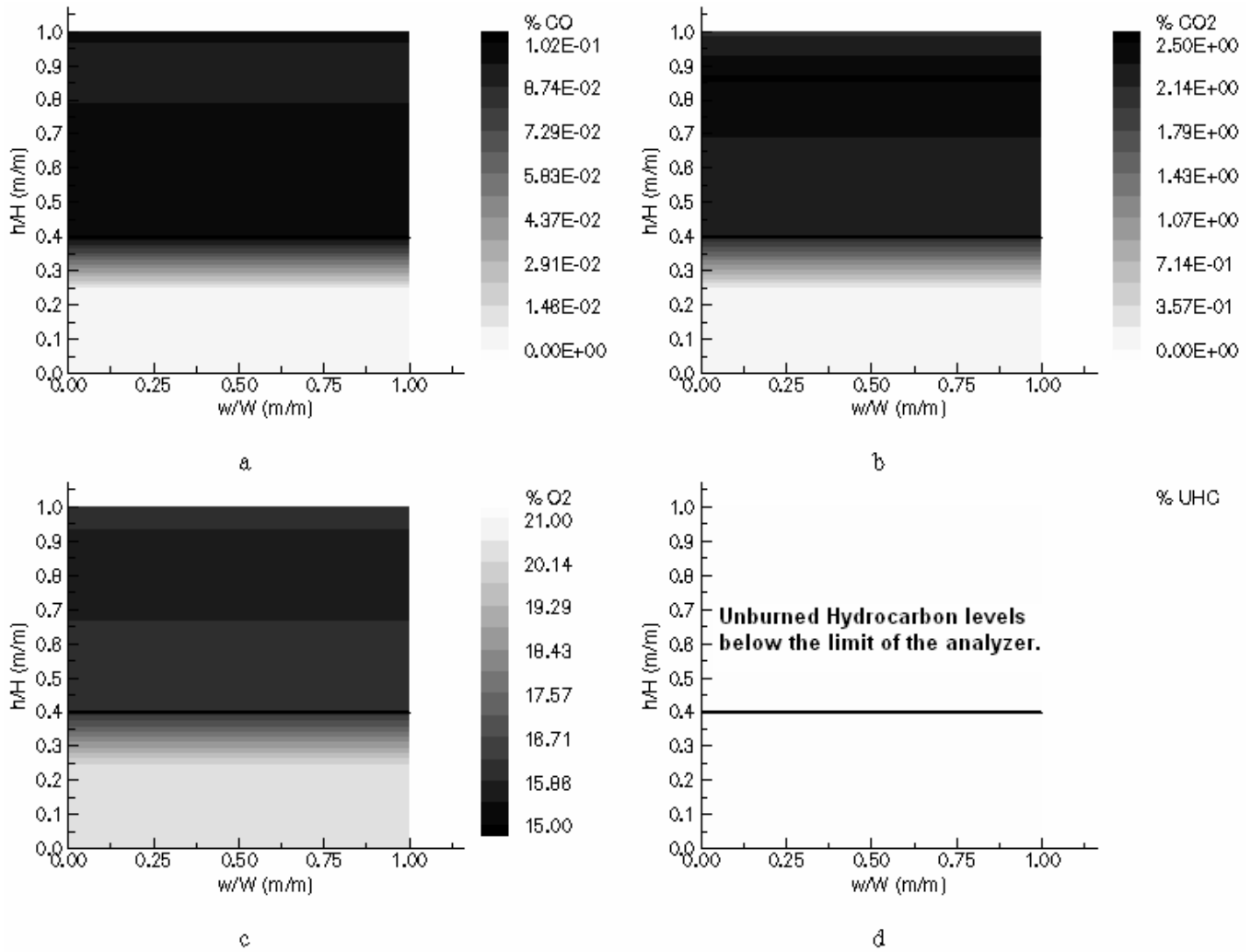


Figure 4-11: Hallway doorway species mole fractions mapping for a heat release rate of 62kW and a burner elevation $h/H_{\text{Door}} = 75\%$. (a) CO, (b) CO₂, (c) O₂ and (d) UHC

For all experiments performed, the species distribution was similar. Figure 4-10 shows a layered distribution of the species concentration. The higher concentrations of CO and CO₂ are observed at the top of the doorway, decreasing rapidly toward the neutral plane location.

When looking at Figure 4-11, the upper layer, above the neutral plane appears to be homogeneous in composition. Mixing must occur along the hallway within the upper layer itself in addition to the mixing between the two layers. It can also be noted that the absence of UHC at the hallway exit plane implies that it was burnt prior to exiting (external burning at the compartment doorway).

The smoke layer build up along the hallway is controlled by the hallway exit soffit depth and the size of the ventilation at this location. Because of this accumulation and due to mixing along the hallway, a difference in the spatial uniformity of the exhaust gas composition can be seen between the compartment doorway and the hallway doorway.

CHAPTER 5 – SUMMARY AND CONCLUSIONS

5.1 INTRODUCTION

The objective of the present study was to gain a better understanding of the geometrical parameters affecting the species generation and transport from enclosure fires connected to an enclosed adjacent space. The fire source elevation was the principal parameter investigated. To achieve the goal set by this research, experiments were conducted with a half-scale ISO 9705 compartment connected to a 6.1 m long hallway in a head-on configuration. Experiments were performed with fixed ventilation conditions (i.e., a baseline doorway at the compartment/hallway interface and a narrow doorway at the hallway exit plane) and three fire source elevations were investigated (i.e., $h/H_{\text{Door}}=12.5\%$, $h/H_{\text{Door}}=50\%$ and $h/H_{\text{Door}}=75\%$). Gaseous propane was used to simulate buoyancy driven fires with heat release rates ranging from 20 kW to 150 kW.

The analysis of the results was separated into two parts. The first part was the analysis of the species generation based on the measurements obtained at the compartment/hallway interface doorway only. The second part was a carbon monoxide transport analysis along the hallway. This part consisted in comparing the measurements obtained at the compartment/hallway interface doorway to the ones obtained at the hallway doorway exit.

Measurements of local species mole fraction, local gas pressure (for gas velocity calculations) and local gas temperature were performed across the surface of both doorways. With the assumption that a steady state was reached, time averaged values of the measurements were obtained at each sampling point. An integration scheme over the doorway cross-sections was used to calculate the species mass flow rate through the openings.

5.2 STUDY OF SPECIES GENERATION IN AN ATTACHED COMPARTMENT

The study of species generation from fires has been investigated by several researchers. Various test apparatus were used, from bench-scale (Beyler [1983, 1986], Toner et al. [1987] and Morehart et al. [1990]), to small-scale (Gottuk [1992], Pitts [1994] and Wieczorek [2003]), and full-scale (Tewarson [1984], Blomqvist [2001]). Beyler [1983], the trail blazer in this field of study, proposed to correlate the species generation to a meaningful fuel-to-air ratio. The methodology, termed the global equivalence ratio concept, consists of correlating the species yields to the global equivalence ratio. The concept was developed based on bench-scale hood experiment data for which the global equivalence ratio was assumed equal to the plume equivalence ratio.

To extend this concept to compartment test data, the global equivalence ratio must equal the plume equivalence ratio. For this to be true, all the air drawn inside the compartment must be entrained through the fire plume and the upper layer gas must be well mixed.

Nelson et al. [1990], Pitts [1995] and Wieczorek [2003] observed spatial variations in the species mole fraction measurements performed at the doorway of enclosure fires.

In the study by Wieczorek [2003] the species mass flow rates (and yields) were obtained by performing detailed mapping of the gas composition, gas velocity and gas temperature and integrating over the area of the exiting portion of the doorway. The global equivalence ratio concept was determined inappropriate for this scenario. Indeed, the species mole fraction mapping indicated that, in addition to the spatial variations of the gas composition, not all the air drawn inside the compartment was entrained into the fire plume. To correlate the species yields based on the combustion within the compartment for the range of ideal heat release rates studied, Wieczorek [2003] developed an alternative methodology based on a non dimensional heat release rate $\tilde{Q}$. This new parameter was defined as the ratio of the ideal heat release rate, $\dot{Q}_{ideal}$, divided

by the heat release rate required for the flame to reach the top of the doorway, $\dot{Q}_{\text{Flame Extensions}}$. Due to a lack in flame length calculation methods for fire in enclosures, $\dot{Q}_{\text{Flame Extensions}}$ was determined experimentally for each ventilation size studied. The results showed good correlation for all four species studied (CO, CO₂, O₂ and UHC). However this parameter was developed using the data obtained from the compartment study in a stand-alone configuration.

Comparing the data of the present study to the data of the study conducted by Wieczorek [2003] revealed differences in the fire dynamic behavior, for identical geometric parameters and heat release rate. These differences in the fire scenario were attributed to the addition of the hallway and its doorway. The presence of a confined adjacent space changed the conditions directly outside of the compartment. The boundary properties (walls and ceiling) and the smoke layer developed along the hallway, in part controlled by the presence of a soffit and a doorway at the end of the hallway, contributed to changing the flow dynamic and the air entrainment pattern. For two of the fire source elevations investigated ($h/H_{\text{door}} = 12.5\%$ and $h/H_{\text{door}} = 50\%$) the smoke layer reached the floor as the heat release rate was increased. This phenomenon compromised the two layer flow dynamic along the hallway for which the test procedure and the measurement technique were developed. The study was therefore restricted to heat release rates representing fire scenarios prior to the occurrence of this phenomenon. However, for the burner at $h/H_{\text{door}} = 75\%$, the smoke layer never reached the floor and external burning was observed.

The study of the fire source elevation, restricted to fires contained within the compartment, allowed drawing qualitative conclusions on its effects on the carbon monoxide production. As the ideal heat release rate was increased, the carbon monoxide yield increased for each burner elevation. The rate of increase in the CO production was faster as the burner was raised. Moreover, for equal ideal heat release rate, $\dot{Q}_{\text{Ideal}}$ the carbon monoxide yields were higher as the burner was elevated. These behaviors were related to the proportion of fuel burning with sufficient oxygen to fuel burning in the

upper layer within oxygen vitiated gas. Forcing most of the fuel to burn within the upper layer by either increasing the fuel mass flow rate (ideal heat release rate) or elevating the fire source resulted in an increase in the CO production.

From the observation that the CO yields consistently increased with the ideal heat release rate for fire contained inside the compartment, a new definition was given to the non dimensional heat release rate $\hat{Q}$ to correlate the data of this study. $\hat{Q}$ was then defined as the ratio of the ideal heat release rate, $\dot{Q}_{ideal}$, divided by the heat release rate corresponding to the maximum CO production, $\dot{Q}_{MaxCO}$. However, the maximum CO yield measured was different for each configuration. The non dimensionalized CO yield based on the maximum CO yield measured was chosen as the dependant variable. Presenting the results in this manner collapsed the data from the three burner elevations onto a single curve. A correlation based on a regression analysis was developed using the software CurveExpert (Version 1.34). By performing a carbon atom balance to the compartment assuming no soot was generated (for lack of measurements), a correlation was developed for the carbon dioxide yield based on the correlation obtained for the carbon monoxide. The correlation over predicted the carbon dioxide since evidently soot was generated. However, similar trends were observed between the data and the predictions.

The maximum carbon monoxide yield and the ideal heat release rate corresponding to it used to correlate the data were obtained experimentally for lack of calculation methods.

5.3 CARBON MONOXIDE TRANSPORT STUDY SUMMARY

A transport study of the carbon monoxide along the hallway was conducted for the three burner elevations. Reported in all previous studies performed on the transport of CO to adjacent spaces, confined or not, (Gottuk [1992], Lönnermark et al. [1997], Ewens [1994], Lattimer [1996] and Wieczorek [2003]) external burning and fluid dynamics played key roles. The presence of flaming outside the compartment implies the presence

of sufficient oxygen and high temperatures resulting in the oxidation of the carbon monoxide generated inside the compartment to carbon dioxide. For such instance, the carbon monoxide levels transported to the adjacent space were reported to be lower than the ones generated within the enclosure. In the absence of external burning, the oxidation reaction considered “frozen” does not alter the carbon monoxide production. The CO levels generated were then transported to the remote location.

For the burner elevations $h/H_{\text{Door}}=12.5\%$ and $h/H_{\text{Door}}=50\%$ no external burning was observed. For the range of ideal heat release rate investigated, the values of the carbon monoxide yields at the compartment doorway, $x=0$ m, and at the hallway doorway, $x=6.1$ m, were very similar.

The same behavior was observed when the fire source was elevated to $h/H_{\text{Door}}=75\%$ with the fire contained to the compartment. However, when external burning was present, in addition to the decrease in the carbon monoxide yields measured at the compartment exit plane, the oxidation reaction from CO to CO₂ occurred. The levels of CO measured at the end of the hallway were consistently lower than the one measured at the compartment doorway.

The flow dynamic along the hallway was also examined. The air entrainment through the compartment doorway was independent of the fire size and burner elevation. However, the size of the hallway doorway, being smaller than the compartment doorway, appeared to control the air entrainment to the fire.

The spatial uniformity of the exhaust gas at both doorways was also compared. For all tests performed, a gradient in the species concentration through the compartment doorway was observed. The highest mole fractions of CO and CO₂ and the lowest O₂ mole fractions were observed at the top of the doorway. The development of a smoke layer along the hallway controlled by the hallway ventilation and hallway soffit allowed the gas to mix. A homogenous exhaust gas composition was observed at the hallway doorway.

CHAPTER 6 – RECOMMENDATIONS FOR FUTURE WORK

The present research resulted in a better understanding of the parameters controlling the species generation and transport from compartment fires. Qualitative conclusions were drawn based on observation of the fire scenarios and the trends in the data. Although conducive, this study revealed new aspects of the fire dynamics.

The study of the fire source elevation revealed the importance of the location of the combustion reaction. Two zones were defined corresponding to two modes of reaction depending on the oxygen availability and the degree of mixing. The first zone consisted of a buoyancy driven diffusion flame burning in air and resulted in products of complete combustion. The second zone referred to the portion of the upper layer where fuel was burning in oxygen vitiated combustion gases and resulted in carbon monoxide generation. Depending on the proportion of fuel burning in zone 1 to the fuel burning in zone 2, more or less CO was formed. A zone model predicting the amount of fuel being burnt in each zone in addition to the degree of completeness of the reaction in each zone would be a good predicting tool for fire safety practices. However, more experiments would be required and a better understanding of the fire dynamic inside the compartment would have to be gained. Measurements of the gas composition need to be made within the upper layer of the compartment as well as within the fire plume for all the scenarios studied.

A limitation on the presence of a two-layer flow along the hallway was observed and attributed to the flow restriction imposed by the hallway ventilation. Indeed, the combustion gases not being able to be exhausted at a sufficient rate occupied most of the hallway volume and compromised the steadiness of the air entrainment. The hallway doorway size resulting in the occurrence of this phenomenon should be further investigated.

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APPENDIX A - UNCERTAINTIES CALCULATIONS

A.1 UNCERTAINTY IN THE DIRTECT MEASURED DATA

Experiments in the present study involved the measurement of several parameters. Estimates of the uncertainties associated with these parameters are given in this section. Table A-1 contains a list of the all the measurements performed, along with the equipment used and the type of possible uncertainties.

Table A-1: List of equipment used and possible sources of uncertainties for each type of measurement performed for the present study

Measurement	Measuring device	Sources of uncertainties
O ₂ mole fraction	O2 Analyzer	- Analyzer repeatability - Analyzer Linearization - Calibration gas - Experimental repeatability
CO ₂ mole fraction	CO/CO2Analyzer	
CO mole fraction	CO/CO2Analyzer	
UHC mole fraction	FID	
Temperature	Thermocouple Type K	- Experimental repeatability - Measurement technique
Gas Pressure	Pressure Transducer	- Experimental repeatability - Accuracy (full scale)
Fuel mass flow rate	Mass flow meter	

A.2.1 Species Mole fractions

The gas analyzers used to measure the species mole fractions were subjected to the sources of uncertainties listed in Table A-1. The values given by the manufacturer are shown in Table A-2.

Table A-2: Uncertainties due to the gas analyzers associated with dry species mole fraction measured

	O ₂ analyzer	CO ₂ analyzer	CO analyzer	FID analyzer*
Analyzer repeatability	± 1 %	± 1 %	± 1 %	± 2 %
Analyzer linearization	0 %	± 2 %	± 2 %	± 0 %
Calibration gas	± 1.5 %	± 1.5 %	± 1.5 %	± 1.5 %
Experimental repeatability**	± 5 %	± 5 %	± 5 %	± 5 %

*Measured directly on a wet basis

**Estimated

Calculations of uncertainties for directly measured data usually assume that all the potential sources of uncertainties are linearly independent. Equation A-1 was used to obtain the uncertainties associated with the measure of dry species mole fractions, Table A-3.

$$\varepsilon^2 = \varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 + \dots \quad (\text{A-1})$$

Table A- 3: Estimated uncertainty in dry species mole fraction measurements

Species	$\varepsilon_{X_{dry}^n}$
dry O ₂ mole fraction	± 5.3 %
dry CO ₂ mole fraction	± 5.7 %
dry CO mole fraction	± 5.7 %
UHC mole fraction*	± 5.6 %

*Measured directly on a wet basis

A.2.2 Gas Temperature:

The temperature measurements obtained from aspirated thermocouples have been reported to have uncertainties between ± 5 % for the cold layer temperatures and ±20% for the upper layer temperatures. [Blevins and Pitts 1999] Wieczorek [2003] used an

estimated uncertainty of $\pm 11.2 \%$ for the calculations based on the temperature in the upper layer since no temperature above 1000K were observed.

A.2.3 Gas Pressure

The bi directional pressure transducers used, Setra Systems Inc. Model 264, were reported to have an accuracy of $\pm 1 \%$ of full-scale. The uncertainty associated with experimental repeatability is assumed to be about $\pm 5 \%$. [Wieczorek 2003] The uncertainty for the gas pressure measurements was then $\pm 5.1 \%$.

A.2.4 Fuel Mass Flow Rate

The reported manufactures uncertainty for the Omega model FMA-1611 mass flow meter is $\pm 1\%$ full scale and $\pm 0.5\%$ experimental repeatability for flow rates between 0 and 250 slpm (. The total uncertainty associated with fuel mass flow rate measurements was therefore 1.1%.

A.3 UNCERTAINTY IN CALCULATED PARAMETERS

Uncertainties in calculated parameters based on measured parameters are usually determined using the Pythagorean summation of discrete uncertainties, Equation A-2.

For a parameter $u = \text{function}(x_1, x_2, \dots, x_n)$, the uncertainty associated with c (in the unit of u) is:

$$\delta u = \sqrt{\left(\delta x_1 \frac{\partial u}{\partial x_1}\right)^2 + \left(\delta x_2 \frac{\partial u}{\partial x_2}\right)^2 + \dots + \left(\delta x_n \frac{\partial u}{\partial x_n}\right)^2} \quad (\text{A-2})$$

In order to report an uncertainty as a percentage, a full scale or maximum value of the parameter u_{ref} must be defined then:

$$\varepsilon_u = \frac{100 \times \delta u}{u_{\text{ref}}}$$

All the calculated parameters involved in this study are functions of the direct measurements listed in Table A-4. In order to perform an uncertainty analysis, the full-scale values (or maximum observed) for each measurement will be used along with their associated estimated uncertainty (ε , in % full-scale and δ , applied to the full scale in unit of the value considered).

Table A-4: List of the direct measurements performed and the full-scale value and their associated estimated uncertainty

Direct Measurement	Full scale or max value measured	ε (%)	δ unit of value
O ₂ mole fraction	0.21	± 5.3	± 0.01113
CO ₂ mole fraction	0.15	± 5.7	± 0.00855
CO mole fraction	0.05	± 5.7	± 0.00285
UHC mole fraction	0.05	± 5.6	± 0.0028
Temperature	1000 K	± 11.2	± 112 K
Gas Pressure	25 Pa	± 5.1	± 1.275 Pa
Fuel mass flow rate	0.0075 kg/s	± 1.1	± 0.000082 kg/s

A.3.1 Wet Species Mole Fractions

The oxygen and the carbon monoxide/carbon dioxide gas analyzers make measurements on a dry gas basis. A correction for the water content is obtained from the assumption that the molar ratio, c , of H₂O to CO₂ at any equivalence ratio is equal to the calculated molar ratio at stoichiometric conditions. [Gottuk 1992, Lattimer 1996, McKay 2002] The water mole fraction is then obtained from the dry carbon dioxide mole fraction. Gottuk [1992] estimated that this local water mole fraction calculation was valid to ± 6 %. In order to later be able to calculate the uncertainties added to the wet mole fractions estimation using this assumption, the uncertainty on the ratio c is calculated.

$$c = \frac{X_{\text{H}_2\text{O}}}{X_{\text{dry}}^{\text{CO}_2}} = \frac{4}{3}$$

$$\frac{\partial c}{\partial X_{\text{dry}}^{\text{CO}_2}} = -\frac{X^{\text{H}_2\text{O}}}{\left(X_{\text{dry}}^{\text{CO}_2}\right)^2} \quad \text{And} \quad \frac{\partial c}{\partial X^{\text{H}_2\text{O}}} = \frac{1}{X_{\text{dry}}^{\text{CO}_2}}$$

so

$$\delta c = \sqrt{\left(\delta X^{\text{H}_2\text{O}} \frac{\partial c}{\partial X^{\text{H}_2\text{O}}}\right)^2 + \left(\delta X_{\text{dry}}^{\text{CO}_2} \frac{\partial c}{\partial X_{\text{dry}}^{\text{CO}_2}}\right)^2}$$

For $X_{\text{dry}}^{\text{CO}_2} = 0.15$ the water mole fraction is $X^{\text{H}_2\text{O}} = 0.2$ and $\delta X^{\text{H}_2\text{O}} = \pm 0.0012$

$$\delta c = \pm 0.11$$

Therefore, the uncertainty associated with c is $\pm 8.27 \%$.

The wet species mole fractions are then determined from the measured dry species mole fractions from Equation A-3, taking into account the measured dry carbon monoxide mole fraction. [Lattimer,1996]

$$X_{\text{wet}}^n = \frac{X_{\text{dry}}^n}{1 + c \left(X_{\text{dry}}^{\text{CO}} + X_{\text{dry}}^{\text{CO}_2} \right)} \quad (\text{A-3})$$

$$\frac{\partial X_{\text{wet}}^n}{\partial X_{\text{dry}}^n} = \frac{1}{1 + c \left(X_{\text{dry}}^{\text{CO}} + X_{\text{dry}}^{\text{CO}_2} \right)}$$

$$\frac{\partial X_{\text{wet}}^n}{\partial X_{\text{dry}}^{\text{CO}}} = -\frac{c X_{\text{dry}}^n}{\left(1 + c \left(X_{\text{dry}}^{\text{CO}} + X_{\text{dry}}^{\text{CO}_2} \right) \right)^2}$$

$$\frac{\partial X_{\text{wet}}^n}{\partial X_{\text{dry}}^{\text{CO}_2}} = -\frac{c X_{\text{dry}}^n}{\left(1 + c \left(X_{\text{dry}}^{\text{CO}} + X_{\text{dry}}^{\text{CO}_2} \right) \right)^2}$$

$$\frac{\partial X_{\text{wet}}^n}{\partial c} = -\frac{\left(X_{\text{dry}}^{\text{CO}} + X_{\text{dry}}^{\text{CO}_2} \right) X_{\text{dry}}^n}{\left(1 + c \left(X_{\text{dry}}^{\text{CO}} + X_{\text{dry}}^{\text{CO}_2} \right) \right)^2}$$

So

$$\delta X_{\text{wet}}^n = \sqrt{\left(\delta X_{\text{dry}}^n \frac{\partial X_{\text{wet}}^n}{\partial X_{\text{dry}}^n} \right)^2 + \left(\delta X_{\text{dry}}^{\text{CO}} \frac{\partial X_{\text{wet}}^n}{\partial X_{\text{dry}}^{\text{CO}}} \right)^2 + \left(\delta X_{\text{dry}}^{\text{CO}_2} \frac{\partial X_{\text{wet}}^n}{\partial X_{\text{dry}}^{\text{CO}_2}} \right)^2 + \left(\delta c \frac{\partial X_{\text{wet}}^n}{\partial c} \right)^2}$$

Using the values from Table A-4, the uncertainties for each wet species mole fractions were calculated and are shown in Table A-5.

With the assumption that the gas composition consisted of oxygen, carbon dioxide, carbon monoxide, unburned hydrocarbons, water, and nitrogen, the wet mole fraction of nitrogen is determined by Equation A-4,

$$X_{\text{wet}}^{N_2} = 1.0 - \sum X_{\text{wet}}^n \quad (\text{A-4})$$

So

$$\delta X_{\text{wet}}^{N_2} = \sqrt{\left(\sum (\delta X_{\text{wet}}^n)^2 \right)}$$

Table A-5: Uncertainties associated to the wet species mole fraction calculation

Species	X^n	ε	δ unit of value
Wet O ₂ mole fraction	0.0336	± 5.65 %	± 0.0018
Wet CO ₂ mole fraction	0.0674	± 6.03 %	± 0.004
Wet CO mole fraction	0.0135	± 6.03 %	± 0.0008
UHC mole fraction*	0.0	± 5.6 %	± 0.0
Wet N ₂	0.7593	± 13.1 %	± 0.0994
H ₂ O	0.1259	± 6 %.	± 0.0075

A.3.2 Molecular Weight of Mixture

The molecular weight of the mixture is determined from the following Equation A-5.

$$MW^{\text{mix}} = \sum X^n MW^n \quad (\text{A-5})$$

Assuming that the molecular weight of each species is well defined, the uncertainty associated to the calculation of the mixture molecular weight is obtained.

$$\varepsilon_{MW^{\text{mix}}} = \sqrt{\sum (\varepsilon_{X_{\text{wet}}^n})^2} = \pm 18.54\%$$

A.3.3 Local Mass Fraction of Species n

The mass fraction of species n is determined by Equation A-6.

$$y^n = \frac{X^n MW^n}{MW^{\text{mix}}} \quad (\text{A-6})$$

Assuming the species molecular weight does not contribute to uncertainty,

$$\left(\frac{\partial y^n}{\partial X_{\text{wet}}^n} \right)_{MW^{\text{mix}}} = \frac{MW^n}{MW^{\text{mix}}} \quad \text{and} \quad \left(\frac{\partial y^n}{\partial MW^{\text{mix}}} \right)_{X_{\text{wet}}^n} = - \frac{X_{\text{wet}}^n MW^n}{(MW^{\text{mix}})^2}$$

$$\delta y^n = \sqrt{\left(\delta X_{\text{wet}}^n \frac{\partial y^n}{\partial X_{\text{wet}}^n} \right)^2 + \left(\delta MW^{\text{mix}} \frac{\partial y^n}{\partial MW^{\text{mix}}} \right)^2} \quad (\text{A-7})$$

Equation A-7 was applied to real data from Appendix-B. For each species and at each point it was applied, the results were similar. The value of the uncertainty associated with the mass fraction for any species is the same as the uncertainty associated with the

A.3.4 Ideal Fire Size

The ideal heat release rate is given Equation A-8

$$\dot{Q}_{\text{ideal}} = \dot{m}_{\text{fuel}} \Delta H_c \quad (\text{A-8})$$

Since the heat of combustion is a constant, the uncertainty in the ideal heat release rate calculation is the same as the uncertainty associated to the measurement of fuel mass flow rate.

$$\varepsilon_{\dot{Q}_{\text{ideal}}} = \varepsilon_{\dot{m}_{\text{fuel}}} = \pm 1.1\%.$$

A.3.5 Gas Density

The density of individual species is determined by Equation A-9.

$$\rho^n = \frac{X^n \text{MW}^n P_{\text{amb}}}{R T} \quad (\text{A-9})$$

The density is a function of the temperature and wet species mole fractions calculated. For the purpose of this analysis, the wet species mole fractions from Appendix-B ($h/H_{\text{door}} = 0.98$ and $w/W = 0.5$) listed in Table A-5 were used and the results are shown in Table A-6. It can be seen that the temperature more than the mole fraction controls the partial density of each species.

$$\varepsilon_T = \pm 11.2\% \text{ so for } T = 729\text{K } \delta T = \pm 81.6\text{K}$$

$$\left(\frac{\partial \rho^n}{\partial X^n} \right)_T = \frac{\text{MW}^n P_{\text{amb}}}{R T} \quad \text{and} \quad \left(\frac{\partial \rho^n}{\partial T} \right)_{X^n} = - \frac{X^n \text{MW}^n P_{\text{amb}}}{R T^2}$$

So,

$$\delta \rho^n = \sqrt{\left(\left(\frac{\partial \rho^n}{\partial X^n} \right)_T \delta X^n \right)^2 + \left(\left(\frac{\partial \rho^n}{\partial T} \right)_{X^n} \delta T \right)^2}$$

Table A-6: Estimated Uncertainties in Species Density.

Species n	ε_{ρ^n} (%)
O ₂	± 11.2 %
CO ₂	± 11.2 %
CO	± 11.2 %
UHC	± 11.2 %
N ₂	± 14.2 %
H ₂ O	± 11.22 %

The total gas density is the summation of each of the individual species densities, therefore, the uncertainty in the total gas density is obtained from:

$$\varepsilon_{\rho, \text{total}} = \sqrt{\sum (\varepsilon_{\rho_i})^2} = \pm 28.8 \%$$

A.3.6 Gas Velocity

From a simple Bernoulli's analysis the local gas velocity is determined by Equation A-10.

$$V = \sqrt{\frac{2 \Delta P}{\rho_{\text{air}}}} \quad (\text{A-10})$$

Since the local air density is a function of the local air temperature, therefore,

$$V = \sqrt{\frac{2 \Delta P}{\rho_{\text{air}}}} = \sqrt{\frac{2 \Delta P}{\left(\frac{353}{T}\right)}} = \sqrt{\frac{2 \Delta P T}{353}}$$

The maximum observed value of the temperature and the full scale value of the pressure transducer are used to estimate the uncertainty associated with the gas velocity calculation.

$$\varepsilon_T = \pm 11.2\% \text{ so for } T = 1000 \text{ K and } \delta T = \pm 112 \text{ K}$$

$$\varepsilon_{\Delta P} = \pm 5.1\% \text{ so for } \Delta P = 25 \text{ Pa and } \delta \Delta P = \pm 1.275 \text{ Pa}$$

$$\left(\frac{\partial V}{\partial \Delta P}\right)_T = 0.93 \frac{T}{353 \sqrt{\frac{2 \Delta P T}{353}}} \quad \text{and} \quad \left(\frac{\partial V}{\partial T}\right)_P = 0.93 \frac{\Delta P}{353 \sqrt{\frac{2 \Delta P T}{353}}}$$

$$\delta V = \sqrt{\left(\left(\frac{\partial V}{\partial \Delta P}\right)_T \delta \Delta P\right)^2 + \left(\left(\frac{\partial V}{\partial T}\right)_P \delta T\right)^2} = \pm 0.284 \text{ m/s}$$

$$\varepsilon_V = \pm 6.15\%$$

The calculated uncertainty in the velocity measurement is estimated to be $\pm 6.15\%$.

A.3.7 Species mass flow rates

The species mass flow rates through the doorways are calculated following the procedure described in section 2.3.3.

$$\dot{m}_{\text{out}}^n = \iint \rho^n V dA$$

This calculation involves an integration based on the measurement grid. Both the uncertainties in the measurements at each points and the uncertainty associated with the grid resolution must be accounted for in the calculation of the uncertainties associated with the species mass flow rates. They were assumed to be linearly independent.

$$\varepsilon_V = \pm 6.15\% \text{ sor for } V = 11 \text{ m/s and } \delta_V = \pm 0.68 \text{ m/s}$$

Using the species densities values from Table A-6 and the point from Appendix-B ($h/H_{\text{door}} = 0.98$ and $w/W = 0.5$), the uncertainty associated with the calculation of the species densities multiplied by the velocity (full scale) for one sampled points of the measurement grid are listed in Table A-7.

Wieczorek [2003] determined the uncertainty introduced by the grid resolution in the calculation of the species mass flow rates for the Baseline and Narrow doorway to be no more than $\varepsilon_{\text{GR}} = 10\%$. The results are shown in Table A-8.

Table A-7: Estimated uncertainties in species density x velocity.

Specie n	$\varepsilon_{\rho^n V}$ (%)
O ₂	± 12.8 %
CO ₂	± 12.8 %
CO	± 12.8 %
UHC	± 12.8 %
N ₂	± 15.5 %
H ₂ O	± 12.8 %

$$\varepsilon_{\dot{m}_{out}^n} = \sqrt{\varepsilon_{\rho^n V}^2 + \varepsilon_{GR}^2}$$

Table A-8: Estimated uncertainties in species mass flow rates.

Specie n	$\varepsilon_{\dot{m}_{out}^n}$ (%)
O ₂	± 16.2 %
CO ₂	± 16.2 %
CO	± 16.2 %
UHC	± 16.2 %
N ₂	± 18.5 %
H ₂ O	± 16.2 %

A.3.8 Total mass flow rate out

The total mass flow rate flowing out of a ventilation is given by:

$$\dot{m}_{out}^{tot} = \sum \dot{m}_{out}^n$$

Therefore, the uncertainty associated with its measurement is given by:

$$\varepsilon_{\dot{m}_{out}^{tot}} = \sqrt{\sum \varepsilon_{\dot{m}_{out}^n}^2} = 40.7\%$$

A.3.9 Species Yields

The species yields based on the fuel mass flow rate obtained from the fuel mass flow meter measurements were calculated using Equation A-11

$$Y^n = \frac{\dot{m}_{out}^n}{\dot{m}_{fuel}} \quad (A-11)$$

So

$$\left(\frac{\partial Y^n}{\partial \dot{m}_{out}^n} \right)_{\dot{m}_{fuel}} = \frac{1}{\dot{m}_{fuel}} \text{ And } \left(\frac{\partial Y^n}{\partial \dot{m}_{fuel}} \right)_{\dot{m}_{out}^n} = - \frac{\dot{m}_{out}^n}{\dot{m}_{fuel}^2}$$

And using the same data point used in the previous sections, the uncertainties associated with the calculation of the species yields were obtained; Table A-9.

Table A-9: Estimated uncertainties in species yields.

Specie n	$\varepsilon_{\dot{m}_{out}^n}$ (%)
O ₂	± 25.5 %
CO ₂	± 25.5 %
CO	± 25.5 %

APPENDIX B – RAW DATA FILES

The raw data files, along with the input files, data reduction code and results worksheet are located on the Mechanical Engineering Department server:

Network: RFLOW8 User File:

R:\lmounaud\MasterDegree\DATA ANALYSIS Burner elevation

The results obtained for the test number 0408310 are shown in the following pages. This test was performed a fire source elevation of 75% of the doorway height and with a fuel mass flow rate of 31 slpm. This fire corresponded to an ideal heat release rate of 43 kW. These results are reported in Chapter 3 and 4.

TEST NUMBER 0408310

RESULTS AT COMPARTMENT DOORWAY: BASELINE

TEMPERATURES (K)

Burner Elevation / Doorway Height	0.75
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Fuel mass flow rate based on MFM reading	31.0	slpm
Fuel mass flow rate based on MFM reading	9.30E-04	kg/sec
Fire Size based on MFM reading	43.07	kW
Fuel mass flow rate based on O2 depleted	1.20E-03	kg/sec
Fire Size based on O2 depleted	52.46	kW

Air Entrainment (Mass Balance)	6.76E-02	kg/sec
Mixture Molecular Weight (INFLOW)	28.79	kg/kmol

Exhaust gas mass flow rate	6.85E-02	kg/sec
Mixture Molecular Weight (OUTFLOW)	28.56	kg/kmol

Global Equivalence Ratio	0.22
Plume Equivalence Ratio (O2 used)	0.82

Compartment Side:

Top 1st	763
2nd	705
3rd	768
4th	655
5th	612
6th	584
7th	607
8th	548
Bottom 9th	541

Ambient	294
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Ceiling 1	518
Ceiling 2	506
Ceiling 3	493

Integrated Averages (OUTFLOW)	CO	CO2	O2	UHC	N2	H2O
Avg Wet mole fraction (%)	0.50	2.72	13.81	0.23	78.44	4.30
Avg Wet mass fraction (%)	0.49	4.19	15.48	0.23	76.90	2.71
Species mass flow rate (kg/s)	3.36E-04	2.87E-03	1.06E-02	1.56E-04	5.27E-02	1.85E-03
Species Yield based on MFM (g/gfuel)	0.332	2.74	4.41	0.17		
Species Yield based on O2 (g/gfuel)	0.254	2.09	3.47	0.13		

Integrated Averages (INFLOW)	CO	CO2	O2	UHC	N2	H2O
Avg Wet mole fraction (%)	0.04	0.31	19.57	0.00	79.60	0.47
Avg Wet mass fraction (%)	0.04	0.48	21.76	0.00	77.43	0.30
Species mass flow rate (kg/s)	2.69E-05	3.24E-04	1.47E-02	0.00E+00	5.23E-02	2.00E-04

Neutral Plane Average (Vel Profiles)	0.38	m
Neutral Plane Average (J&T)	0.39	m

NP Height Left	0.389	m
NP Height Center	0.380	m
NP Height Right	0.384	m

Based on velocity profiles

Based on velocity profiles

Based on velocity profiles

Carbon Error:	-26.30	%
Carbon Error Based on O2 depleted:	2.36	%

Air Entrainment (Mass Balance)	6.76E-02	kg/sec
Air Entrainment (based on Reverse CO2)	6.67E-02	kg/sec
Air Entrainment (based on Reverse O2)	5.55E-02	kg/sec
Air Entrainment (based on $0.52 \cdot A \cdot \sqrt{h}$)	1.27E-01	kg/sec

Based on velocity profiles

Valid only if equivalence ratio is below one!

Valid only if equivalence ratio is below one!

TEST NUMBER 0408310

MAPPING AT COMPARTMENT DOORWAY: BASELINE

CO Mole fraction (%)

	0.25	0.50	0.75
Top Door	1.410	1.355	1.606
y1	1.410	1.355	1.606
y2	1.393	1.253	1.581
y3	0.305	0.514	0.534
y4	0.048	0.057	0.060
y5	0.042	0.049	0.064
y6	0.052	0.043	0.047
yNP	0.052	0.043	0.047
y7	0.043	0.046	0.038
y8	0.041	0.040	0.041
Bot Door	0.041	0.040	0.041

CO2 Mole fraction (%)

	0.25	0.50	0.75
Top Door	8.04	6.74	7.83
y1	8.04	6.74	7.83
y2	7.82	6.36	7.74
y3	2.01	3.20	3.04
y4	0.35	0.40	0.40
y5	0.32	0.36	0.42
y6	0.38	0.32	0.33
yNP	0.38	0.32	0.33
y7	0.33	0.35	0.29
y8	0.32	0.31	0.31
Bot Door	0.32	0.31	0.31

N2 Mole fraction (%)

	0.25	0.50	0.75
Top Door	75.93	75.93	77.02
y1	75.93	75.93	77.02
y2	75.93	75.93	77.10
y3	78.72	78.72	77.91
y4	79.61	79.61	79.55
y5	79.63	79.63	79.56
y6	79.58	79.58	79.62
yNP	79.58	79.58	79.62
y7	79.61	79.61	79.56
y8	79.61	79.61	79.60
Bot Door	79.61	79.61	79.60

O2 Mole fraction (%)

	0.25	0.50	0.75
Top Door	1.34	3.36	1.20
y1	1.34	3.36	1.20
y2	1.81	4.54	1.38
y3	15.82	13.22	13.39
y4	19.46	19.38	19.37
y5	19.53	19.47	19.34
y6	19.40	19.53	19.57
yNP	19.40	19.53	19.57
y7	19.53	19.51	19.67
y8	19.56	19.59	19.57
Bot Door	19.56	19.59	19.57

UHC Mole fraction (%)

	0.25	0.50	0.75
Top Door	0.692	0.719	0.906
y1	0.692	0.719	0.906
y2	0.777	0.611	0.863
y3	0.072	0.201	0.145
y4	0.000	0.000	0.000
y5	0.000	0.000	0.000
y6	0.000	0.000	0.000
yNP	0.000	0.000	0.000
y7	0.000	0.000	0.000
y8	0.000	0.000	0.000
Bot Door	0.000	0.000	0.000

H2O Mole fraction (%)

	0.25	0.50	0.75
Top Door	12.59	12.59	10.80
y1	12.59	12.59	10.80
y2	12.28	12.28	10.14
y3	3.08	3.08	4.95
y4	0.53	0.53	0.61
y5	0.48	0.48	0.55
y6	0.58	0.58	0.49
yNP	0.58	0.58	0.49
y7	0.49	0.49	0.53
y8	0.48	0.48	0.46
Bot Door	0.48	0.48	0.46

Temperature (K)

	0.25	0.50	0.75
Top Door	732	729	772
y1	732	729	772
y2	827	846	841
y3	785	811	831
y4	742	766	779
y5	715	744	748
y6	654	701	672
yNP	654	701	672
y7	589	599	586
y8	562	575	572
Bot Door	562	575	572

Velocity (m/s)

	0.25	0.50	0.75
Top Door	0.00	0.00	0.00
y1	1.85	1.93	2.22
y2	1.96	1.95	2.27
y3	1.81	2.03	2.11
y4	1.43	1.57	1.65
y5	1.20	1.34	1.44
y6	0.86	0.97	0.84
yNP	0.00	0.00	0.00
y7	-0.48	-0.36	-0.37
y8	-0.61	-0.57	-0.75
Bot Door	-0.61	-0.57	-0.75

Appendix B. Raw Data Files

TEST NUMBER 0408310

RESULTS AT HALLWAY DOORWAY:

NARROW

TEMPERATURES (K)

Compartment Side:

Fuel mass flow rate based on MFM reading	31.0	slpm
Fuel mass flow rate based on MFM reading	9.30E-04	kg/s
Fire Size based on MFM reading	43.07	kW
Fuel mass flow rate based on O2 depleted	7.50E-04	kg/s
Fire Size based on O2 depleted	32.71	kW

Air Entrainment (Mass Balance)	6.46E-02	kg/s
Mixture Molecular Weight (INFLOW)	28.83	kg/kmol

Exhaust gas mass flow rate	6.67E-02	kg/s
Mixture Molecular Weight (OUTFLOW)	28.66	kg/kmol

Global Equivalence Ratio	0.23
Plume Equivalence Ratio (O2 Used)	1.31

Top 1st	740
2nd	659
3rd	797
4th	681
5th	637
6th	609
7th	634
8th	573
Bottom 9th	564

Ambient	295
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Ceiling 1	527
Ceiling 2	515
Ceiling 3	503

Integrated Averages (OUTFLOW)	CO	CO2	O2	UHC	N2	H2O
Avg Wet mole fraction (%)	0.29	1.81	16.25	0.00	78.84	2.80
Avg Wet mass fraction (%)	0.28	2.78	18.14	0.00	77.03	1.76
Species mass flow rate (kg/s)	1.90E-04	1.86E-03	1.21E-02	0.00E+00	5.14E-02	1.17E-03
Species Yield based on MFM (g/gfuel)	0.204	1.62	2.75	0.00		
Species Yield based on O2 (g/gfuel)	0.251	1.99	3.50	0.00		

Integrated Averages (INFLOW)	CO	CO2	O2	UHC	N2	H2O
Avg Wet mole fraction (%)	0.00	0.35	20.44	0.00	78.73	0.47
Avg Wet mass fraction (%)	0.00	0.54	22.69	0.00	76.47	0.30
Species mass flow rate (kg/s)	0.00E+00	3.50E-04	1.47E-02	0.00E+00	4.94E-02	1.91E-04

Neutral Plane Average (Vel Profiles)	0.38	m
Neutral Plane Average (J&T)	0.37	m

NP Height Left	0.378	m
NP Height Center	0.378	m
NP Height Right	0.378	m

Based on velocity profiles

Based on velocity profiles

Based on velocity profiles

Carbon Error Based on MFM:	35.37	%
Carbon Error Based on O2 depleted:	19.87	%

Air Entrainment (Mass Balance)	6.46E-02	kg/sec
Air Entrainment (based on Reverse CO2)	1.01E-01	kg/sec
Air Entrainment (based on Reverse O2)	7.68E-02	kg/sec
Air Entrainment (based on $0.52 \cdot A \cdot \sqrt{h}$)	6.18E-02	kg/sec

Based on velocity profiles

Valid only if equivalence ratio is below one!

Valid only if equivalence ratio is below one!

TEST NUMBER 0408310
MAPPING AT HALLWAY DOORWAY: NARROW

CO Mole fraction (%)

	0.50
Top Door	0.313
y1	0.313
y2	0.313
y3	0.299
y4	0.192
yNP	0.192
y5	0.000
Bot Door	0.000

CO2 Mole fraction (%)

	0.50
Top Door	1.86
y1	1.86
y2	1.96
y3	1.88
y4	1.29
yNP	1.29
y5	0.35
Bot Door	0.35

N2 Mole fraction (%)

	0.50
Top Door	78.80
y1	78.80
y2	78.77
y3	78.84
y4	79.11
yNP	79.11
y5	78.73
Bot Door	78.73

O2 Mole fraction (%)

	0.50
Top Door	16.14
y1	16.14
y2	15.93
y3	16.07
y4	17.44
yNP	17.44
y5	20.44
Bot Door	20.44

UHC Mole fraction (%)

	0.50
Top Door	0.000
y1	0.000
y2	0.000
y3	0.000
y4	0.000
yNP	0.000
y5	0.000
Bot Door	0.000

H2O Mole fraction (%)

	0.50
Top Door	2.89
y1	2.89
y2	3.03
y3	2.91
y4	1.97
yNP	1.97
y5	0.47
Bot Door	0.47

Temperature (K)

	0.50
Top Door	464
y1	464
y2	445
y3	426
y4	359
yNP	359
y5	294
Bot Door	294

Velocity (m/s)

	0.50
Top Door	2.53
y1	2.53
y2	1.69
y3	1.32
y4	0.54
yNP	0.00
y5	-0.73
Bot Door	-0.73