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Effectiveness of a Flanged and Unflanged Small Rectangular Capturing Hood

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Effectiveness of a Flanged and Unflanged Small Rectangular Capturing Hood

Stephen Philip Kasberger

**Thesis Submitted to
The Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of requirements
for the degree of**

**Master of Science
in
Industrial Hygiene**

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2012**

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Industrial Hygiene; Occupational Safety and Health**

ABSTRACT

Effectiveness of a Flanged and Unflanged Small Rectangular Capturing Hood

Stephen Philip Kasberger

Capturing hoods are an important tool for protecting workers from hazardous airborne exposures and often preferred because their small sizes offers little interference to the worker or process. Current ventilation guidelines for capturing hood assume that exceeding a recommended capture velocity ensures an acceptable degree of effectiveness. That assumption has little basis in scientific studies. This study investigated the effectiveness of a 6 inch by 12 inch rectangular capturing hood centered on a work table with a manikin acting as a surrogate for a worker.

The study utilized a tracer gas (Freon-134a) to evaluate effectiveness of a capturing hood at three different hood airflows (Q), two different cross draft velocities (V_{cross}), and with the presence or absence of a flange (Flange). The tested air flows through the hood produced velocities at the leading edge of the source (V_x) of approximately 40, 100, and 140 fpm, as measured with a constant temperature anemometer. The study was conducted inside of a 9 ft high, 12 ft wide, 50 ft long wind tunnel with the manikin's back to the cross draft. Tracer gas was released from a custom made source located 11" in front of the capturing hood. The manikin was heated and "breathed." Its hands were positioned on either side of the source.

Breathing zone samples from the nose (C_{nose}) and mouth (C_{mouth}) of the manikin were collected simultaneously to evaluate the protection efficiency of the hood. Samples were also taken simultaneously from inside the duct (C_{duct}) to evaluate the capture efficiency of the hood. Samples were collected in 5 liter Tedlar® bags at a rate of 0.2 lpm over a period of 20 minutes for each sample. Sample bag contents were analyzed by a Gastec FT-IR.

The study used a randomized factorial design with two replications. The results showed that the capturing hood was surprisingly highly effective both in terms of minimizing manikin exposures and minimizing escape of contaminant to the room environment. The concentration of Freon measured in the breathing zone was less than 1 ppm for all tests and mostly was below 0.2 ppm, even though the source concentration was over 370,000 ppm and was released at 1.79 lpm. This was true even when the capture velocity was only 50 fpm and the cross draft velocity was 60 fpm. The capture effectiveness of the hood was no less than 90% but the results may not have been reliable due to apparent measurement inaccuracies and imprecision at the Freon levels measured.

The results only apply to this hood under these conditions. Testing under broader ranges of conditions would be necessary before concluding that the capturing hood is always highly effective.

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Table of Contents

ABSTRACT.....	ii
ACKNOWLEDGEMENTS.....	iii
Table of Contents.....	iv
Equations	xii
Chapter 1: Introduction	1
1.1 Background and Significance	1
1.1.1 Velocities in Front of a Capturing Hood.....	2
1.1.2 Measures of Effectiveness	3
1.1.3 Calculating Effectiveness.....	4
1.1.4 Studies of Actual Effectiveness of Hoods.....	6
1.2 Specific Aims	7
1.3 Hypothesis.....	7
Chapter 2: Literature Review	9
2.1. Centerline Velocity, Capture Envelopes.....	9
2.2. Effect of Flanges.....	10
2.3. Efficiency.....	11
2.4. Summary	12
Chapter 3: Apparatus.....	13
3.1 Wind Tunnel.....	13
3.2 Wind Tunnel Cross Draft and Control System	14
3.3 Capture Hood and Control System	14
3.3.1 Air Flow Measurements	17
3.4 Experimental Manikin	19
3.5 Breathing System	21
3.6 Tracer Gas Sampling System	23
3.7 Tracer Gas Measurement System	24
3.8 Tracer Gas Release and Metering System	26
3.9 Point Velocity Measurement System.....	29
3.10 Environmental Measurements	32
Chapter 4: Methods.....	34

4.1	Study Design.....	34
4.1.1	Preliminary Study One	35
4.1.2	Preliminary Study Two	35
4.1.3	Preliminary Study Three.....	36
4.1.4	Main Study	36
4.2	Procedure.....	37
4.2.1	Calibrations prior to testing	37
4.2.2	Preliminary study one: Measurement of V_x	37
4.2.3	Preliminary study two: Measurement of 100% duct	38
4.2.4	Main study	38
4.2.4.1	Prior to each day to testing.....	38
4.2.4.2	Prior to each test.....	38
4.2.4.3	Testing procedure	39
4.2.4.4	After each test.....	39
Chapter 5:	Preliminary study one	40
5.1	Study Design.....	40
5.2	Results.....	41
5.3	Effect of Variables on V_x	42
5.4	Comparison of Measure V_x to V_x Predicted by Equation 2-4.....	44
Chapter 6:	Preliminary study two	47
6.1	Study Design.....	47
6.2	Apparatus and Methods	47
6.2	Results.....	49
6.3	Discussion.....	52
6.4	Conclusions	53
Chapter 7:	Preliminary Study Three.....	54
7.1	Results.....	55
Chapter 8:	Main Study Results.....	57
8.1	Protection Efficiency Results.....	58
8.2	Capture Efficiency Results.....	61
Chapter 9:	Discussion of the Main Study Results	64
9.1	Effect of Independent Variables on $\eta_{le-duct100\%}$	64

9.2	Effect of Independent Variables on η_{e-G}	65
9.3	Comparison of Two Measures of Capture Efficiency: η_{e-g} and $\eta_{e-duct100\%}$	66
9.4	Effect of Independent Variables on PE	69
9.5	Smoke Visualization	70
Chapter 10:	Conclusions	74
10.1	Caveats.....	74
10.2	Recommendations	74
Chapter 11:	References	76
Appendix I.	FTIR Calibration	79
Appendix II.	CTA Calibration and Directional Sensitivity.....	81

Table of Figures

Figure 1-1. Enclosing hood.....	1
Figure 1-2. Capturing hood.....	2
Figure 3-1. Interior lay out of the wind tunnel	13
Figure 3-2. Capturing hood dimensions side view	15
Figure 3-3. Capturing hood dimensions top view	15
Figure 3-4. Dimensions of flanged capturing hood.....	15
Figure 3-5. Front view of the capturing hood and table dimensions	16
Figure 3-6. Side view of the capturing hood and table dimensions	16
Figure 3-7. Pitot traverse tool	19
Figure 3-8. Manikin	20
Figure 3-9. Manikin heating system.....	21
Figure 3-10. Bellows type manikin breathing system.....	22
Figure 3-11. C_{duct} sample location	24
Figure 3-12. Gasmeter FT-IR, gas analysis system.....	25
Figure 3-13. Flow diagram of tracer gas mixture.....	27
Figure 3-14. Tracer gas mixture delivery controls	28
Figure 3-15. Tracer gas mixture release locations	28
Figure 3-16. Tracer gas source	29
Figure 3-17. V_x measurement location with CTA.....	30
Figure 3-18. Detailed description of CTA probe used with permission by Dantec Dynamics.	30
Figure 3-19. CTA principle of operation used with permission by Dantec Dynamics.....	31
Figure 3-20. TSI, Inc. 1125 calibrator	32
Figure 3-21. Psychrometer.....	32
Figure 4-1. Prototypical capturing hood	34
Figure 4-2. Prototypical flanged hood	34
Figure 5-1. V_x Measurements by CTA.	42
Figure 5-2. Graph of measured V_x with a cross draft of 10 fpm and the predicted V_x from Equation 2-3 given in ACGIH's IVM.	45
Figure 5-3. Graph of measured V_x with a cross draft of 60 fpm and the predicted V_x from Equation 2-3 given in ACGIH's IVM.	45
Figure 5-4. Graph of measured V_x with a cross draft of 10 and 60 fpm and the predicted V_x from Equation 2-3 given in ACGIH's IVM.	46
Figure 6-1. Undiluted 100% duct sample results and the corresponding residual value given by the FTIR, error statements were applied at residual >0.02.	48
Figure 6-2. Diluted 100% duct sample results and the corresponding residual values given by the FTIR, not all values show are used in data analysis.	49
Figure 6-3. Diluted Freon duct samples from the 100% duct tests	51
Figure 6-4. Unadjusted capturing efficiency for the 100% duct study calculated using Equation 1-2.....	51
Figure 7-1. Effect of $Rotate_{WTfan}$ on Q	55

Figure 8-1. Measured Freon concentrations at the nose of the manikin and ambient locations for Q and Flange	59
Figure 8-2. Measured Freon concentrations at the mouth of the manikin and ambient locations for Q and Flange	59
Figure 8-3. Protection efficiency based on C_{duct}	60
Figure 8-4. Protection efficiency based on G.....	61
Figure 8-5. Measured Freon concentration in the duct when the tracer gas mixture was being released at the source for Q and Flange.....	62
Figure 8-6. Calculated capture efficiency for Q and Flange based on $C_{duct-100\%}$	63
Figure 8-7. Calculated capture efficiency for Q and Flange based on G.....	63
Figure 9-1. Comparison of the two capture efficiency measures used identified by level of V_{cross}	67
Figure 9-2. Comparison of two measures of capture efficiency	68
Figure 9-3. Comparison of two measure of capture efficiency with four values removed	68
Figure 9-4. Smoke visualization tests at $Freq_{HoodFan} = 23$ and $Rotate_{WTfan} = 930$ with no flange.....	72
Figure 9-5. Smoke Visualization at $Freq_{HoodFan} = 23$ $Rotate_{WTfan} = 930$ with and without a flange.....	73
Figure 9-6. Smoke visualization at $Freq_{HoodFan} = 40$ $Rotate_{WTfan} = 930$ with and without a flange.	73
Figure 9-7. Smoke visualization at $Freq_{HoodFan} = 55$ and $Rotate_{WTfan} = 930$ with and without a flange.	73
Figure 11-1. Calibration curve for the FTIR, combined pre and post calibrations.....	79
Figure 11-2. Residual values associated with the measured Freon concentrations during calibration.	80
Figure 11-3. CTA calibration curve.....	82
Figure 11-4. Directional sensitivity of the CTA when rotated about its axis.....	82

Table of Tables

Table 3-1. Anthropometrically-scaled manikin dimensions	19
Table 3-2. Tracer gas sample locations	23
Table 4-1. Experimental Conditions for preliminary study one and the main study	35
Table 4-2. Conditions for testing 100% capture	36
Table 5-1. Velocity measurements by CTA at the source on the centerline of the hood (V_x) for each condition	41
Table 5-2. Analysis of Variance for dependent variable V_x	43
Table 5-3. V_x calculated from ACGIH's design formula and measured V_x values.	44
Table 6-1. 100% capture study results	50
Table 6-2. Statistics for the Freon concentrations measured during the 100% capture tests	52
Table 7-1. Fixed-effect Analysis of Variance for dependent variable Q	55
Table 8-1. Main study Freon concentrations for each level of independent variable	57
Table 8-2. Descriptive statistics for two measure of PE	60
Table 9-1. Fixed-effect Analysis of Variance for dependent variable $\eta_{e-duct100\%}$	65
Table 9-2. Fixed-effect Analysis of Variance for η_{e-G}	66
Table 9-3. Fixed-effect analysis of variance for the dependent variable C_{mouth}	69
Table 9-4 Fixed-effect analysis of variance for the dependent variable C_{nose}	69
Table 9-5. Result of Smoke Visualization	71
Table 11-1. CTA Calibration	81

Abbreviations

ACGIH	
American Conference of Governmental Industrial Hygienists	1
AIHA	
American Industrial Hygiene Association	1
ANSI	
American National Standards Institute	3
ASTM	
American Society of Testing and Materials	21
C_{ambient}	
Concentration of Freon measured at the inlet of the wind tunnel, used to control for build up of Freon inside the laboratory	23
C_{duct}	
Concentration in the duct, Dependent variable	34
C_{mouth}	
Concentration at the mouth of the manikin, Dependent variable	34
C_{nose}	
Concentration at the nose of the manikin, Dependent Variable	34
FT-IR	
Fourier transform infrared	23
G	
Generation rate of tracer gas expressed in volume per time (lpm)	4
IVM	
Industrial Ventilation Manual	2
LEV	
Local Exhaust Ventilation	1
lpm	
Liters Per Minute	26
η_e	
Capture efficiency	7
$\eta_{e\text{-duct}100\%}$	
Calculated capture efficiency of the hood using the concentration in the duct when 100% capture was assured	5
$\eta_{e\text{-G}}$	
Calculated capture efficiency using the measured generation rate of the source	5
NIST	
National Institute of Standards and Technology	21
NSC	
Natinal Safety Council	1
OSHA	
Occupational Safety and Health Administration	1
PE_{duct}	
Calculated protection efficiency based on the measured concentration of Freon in the duct	6
PE_G	
Calculated protection efficiency based on the calculated concentration of Freon at the source	6
PPM	
Parts Per Million	24

SF_6	
Sulfur Hexafluoride used as a tracer gas	11
V_{face}	
Velocity at the hood face	17

Equations

$$\eta_e = \frac{G'}{G} \dots\dots\dots 1-1$$

$$\eta_{e-G} = \frac{C_{duct}}{\frac{G}{Q}10^6} \dots\dots\dots 1-2$$

$$\eta_{e-duct100\%} = \frac{C_{duct}}{C_{duct-100\%}} \dots\dots\dots 1-3$$

$$PF_{duct} = 1 - \frac{C_{mouth}}{C_{duct}} \text{ or } X(1 - \eta_e) \dots\dots\dots 1-4$$

$$PF_G = 1 - \frac{C_{mouth}}{C_{source}} \text{ or } X(1 - \eta_e) \dots\dots\dots 1-5$$

$$W = 0.75A^{1/2} \dots\dots\dots 2-1$$

$$W = A^{1/2} \dots\dots\dots 2-2$$

$$Q = C_{cap}V(10X^2 + A) \dots\dots\dots 2-3$$

$$V_x = \frac{Q}{C_{cap}(10X^2 + A)} \dots\dots\dots 2-4$$

$$n_e = \frac{C_z}{C_f} \dots\dots\dots 2-5$$

$$V_{cross} = 0.0637(WTrpm) \dots\dots\dots 3-1$$

$$\bar{V}_{duct} = \frac{1}{20} \sum_{i=1}^{20} \sqrt{\frac{VP_i}{df}} \dots\dots\dots 3-2$$

$$df = \left(\frac{SP_{duct} + SP_{atm}}{SP_{std}} \right) \left(\frac{T_{duct}}{T_{std}} \right) \left(\frac{\rho_{air}}{\rho_{std}} \right) \dots\dots\dots 3-3$$

$$\bar{Q} = \bar{V}_{duct}A_{duct} \dots\dots\dots 3-4$$

CHAPTER 1: INTRODUCTION

The purpose of this study is to investigate the capture efficiency and protection efficiency for a small rectangular capturing hood and to quantify the effect a flange has on both the capture and protection efficiency. The hood's performance was quantified through the use of a tracer gas, Freon 134a.

1.1 Background and Significance

Engineering controls, such as local exhaust ventilation (LEV), are important tools in protecting workers from hazardous airborne exposures. In particular, LEV has long been used for controlling worker exposure to vapors, gases, fumes, and particulates and is applied in almost every industry (Dalla Valle & Hatch, 1932). Indeed, the use of such engineering controls are preferred by the Occupational Safety and Health Administrations (OSHA), the National Safety Council (NSC), the American Industrial Hygiene Association (AIHA), the American Conference of Governmental Industrial Hygienists (ACGIH), many other consensus organizations, and governing bodies (National Safety Council, 2002). To be acceptable, LEV hoods should be designed to control the hazard while minimizing interferences to the task being performed.

Figure 1-1. Enclosing hood

LEV hoods may be classified into two categories: “enclosing” and “capturing” hoods. Enclosing hoods completely surround the contaminant source (see Figure 1-1) while capturing hoods

draw air past the containment source with sufficient velocity to capture the contaminant (see Figure 1-2). Each type of LEV hood has advantages and disadvantages for any given application. However, due to the ubiquitous use of capturing hoods in industry (Ellenbecker, Gempel, & Burgess, 1983) they are the focus of this study.

Figure 1-2.Capturing hood

1.1.1 Velocities in Front of a Capturing Hood

Nearly all of the relevant scientific literature published regarding the effectiveness of capturing hoods (Silverman, 1942; Fletcher B. , 1977; Fletcher B. , 1978; Garrison, 1981; Fletcher & Johson, 1982; Flynn & Ellenbecker, 1987; Conroy, Ellenbecker, & Flynn, 1988) have employed the concept of “capture velocity”, which is defined by ACGIH as “the minimum hood-induced air velocity necessary to capture and convey the contaminant into the hood” (ACGIH, 2007). It is assumed that meeting or exceeding recommended velocities ensures an acceptable level of contaminant capture.

These studies measured velocity or developed empirical formulas to predict the velocities induced at a distance in front of a hood (V_x) with the ultimate goal of allowing practitioners to meet target velocities thought to be associated with acceptable performance, such as those given in table 6-1 of ACGIH’s Industrial Ventilation Manual (IVM). These target velocities are loosely based on competing air currents, buoyancy of the contaminant and toxicity of the contaminant. Surprisingly, given their long use, these target velocities have no clear basis in

published empirical data. The assumption that values of V_x are good predictors of hood performance is long held but unsupported by current scientific literature.

Skepticism of the adequacy of control velocities as a surrogate or guidepost to effectiveness is well documented for laboratory hoods. Indeed, ANSI Z9.5 for laboratory fume hoods clearly states that “face velocities are an inadequate indicator of [laboratory] hood performance” (ANSI/AIHA, 2003). For capturing hoods Flynn and Ellenbecker (1986) argued that capture velocity is an inadequate surrogate measure of capturing hood performance. Instead, they recommended capture efficiency, which they defined as “the fraction of airborne contaminant generated per unit time that is captured per unit time” (Ellenbecker, Gampel, & Burgess, 1983) as a more direct measure of hood performance.

1.1.2 Measures of Effectiveness

Clearly the effectiveness of a hood must be determined in terms of its success in reducing exposures to the contaminant it is intended to control. For all hoods, success should be considered in two ways: (1) protecting the user of the hood, and (2) preventing others in the same area from high background concentrations due to escape of contaminants to the room. The former can be described as a “protection efficiency” much like the protection factors for respirators and the latter as a “capture efficiency”.

For respirators, protection factors are generally described as the ratio of the concentration outside the respirator divided by the concentration inside the respirator (TSI Incorporated, 2008). The concentration inside of the respirator is an exposure concentration (e.g., C_{mouth}). The concentration outside the respirator can be compared to any of several different concentrations, such as the concentration of the contaminant as it is released (C_{source}), the concentration of the cloud in the space in between the worker and the hood face (C_{cloud}), and the average concentration if the contaminant is mixed perfectly with the exhaust air (C_{duct}). The protection factor is mathematically related to the protection efficiency. Protection efficiency (PE) is presented as a percentage rather than a whole number and is the measure used in this

study. It should be noted that the protection efficiency is equal to one minus the inverse of the protection factor.

Each of these has disadvantages:

1. $PE = 1 - (C_{\text{mouth}}/C_{\text{source}})$: does not consider generation rate
2. $PE = 1 - (C_{\text{mouth}}/C_{\text{cloud}})$: the boundaries of the cloud would be difficult to specify
3. $PE = 1 - (C_{\text{mouth}}/C_{\text{duct}})$: since $C_{\text{duct}} = G/Q$ this formulation would have the paradoxical effect of at some diminishing effect level of Q showing a diminishing PE as the air flow through the hood (Q) increases even if the concentration at the mouth continues to fall to trivial levels.
4. $PE = 1 - (C_{\text{mouth}}/C_{\text{acceptable}})$: would vary with the contaminant and with all factors affecting C_{mouth} .

1.1.3 Calculating Effectiveness

A useful formulation for capture efficiency is much simpler, however may be calculated using two different techniques which both have advantages and disadvantages. The first formulation of efficiency, defined by Flynn and Ellenbecker (1986), is a measure of capture efficiency (η_e), which can be stated mathematically as:

$$\eta_e = \frac{G'}{G} \quad 1-1$$

Where:

G	=	rate of contaminant released by the source (mass or volume per time)
G'	=	rate of contaminant captured by the hood (mass or volume per time)

This formula may be restated in terms of concentration as:

$$\eta_{e-G} = \frac{C_{duct}}{\frac{G}{Q} 10^6} \quad 1-2$$

Where: C_{duct} = Concentration of tracer gas in the duct (ppm)
 G = Controlled rate of release of at the source tracer gas (lpm)
 Q = Air flow through the hood (lpm)

Note that G and G' can be stated as either mass rates or volume rates. For the rest of this investigation it will refer only to volume rates.

Capture efficiency may also be calculated without the measure of generation rate in the equation by assuming that the generation rate is constant. This is accomplished by measuring the concentration of the contaminant in the duct (1) when all the contaminant is released directly into the duct and 100% capture is assured ($C_{duct-100\%}$), and (2) when the contaminant is released at some distance in front of the hood's face (C_{duct}). The ratio of these two measures gives the capture efficiency for the system, which can be expressed mathematically as:

$$\eta_{e-duct100\%} = \frac{C_{duct}}{C_{duct-100\%}} \quad 1-3$$

Where: C_{duct} = Concentration of contaminant in the duct when released at some location in front of the hood's face (ppm)
 $C_{duct-100\%}$ = Concentration of contaminant in the duct when released into the duct (ppm)

By comparing the capture efficiency and protection efficiency of a small rectangular hood with the measured capture velocity, one can determine if a correlation exists between capture velocities and capture effectiveness or protection efficiency. The two measures of protection efficiency chosen and are shown below:

$$PE_{duct} = 1 - \frac{C_{mouth}}{C_{duct}} \text{ or } X(1 - \eta_e) \quad 1-4$$

Where: C_{mouth} = Concentration of tracer gas at manikin's mouth
 η_e = Capture efficiency
 X = Fraction of tracer gas which reaches the breathing zone

$$PE_G = 1 - \frac{C_{mouth}}{C_{source}} \text{ or } X(1 - \eta_e) \quad 1-5$$

Where: C_{source} = Concentration of tracer gas released from source, ppm
 Q = Air flow through the duct
 X = Fraction of tracer gas which reaches the breathing zone

1.1.4 *Studies of Actual Effectiveness of Hoods*

Recently published laboratory “fume” hoods studies have found poor correlations between laboratory hoods’ face velocities and their performance measured by capture efficiency, protection efficiency, and/or smoke visualization (Volin, Joao, Reiman, Party, & Gershey, 1998; Ahn, Woskie, DiBerardinis, & Ellenbecker, 2008). This leads one to question whether capture velocities would show a similar lack of correlation to capture hood performance in terms of capture effectiveness or protection efficiency.

Little scientific attention has been applied to determining the capture efficiency of capturing hoods (Ellenbecker, Gampel, & Burgess, 1983; Flynn & Ellenbecker, 1986). To the author’s knowledge, no empirical studies have investigated the effect on capture efficiency given by a flange.

This study investigated capture efficiency and protection efficiencies for this particular capturing hood’s performance under the conditions tested.

1.2 Specific Aims

The goals of this study are to quantify the capture efficiency (η_e) and protection efficiency (PE) of a particular small rectangular capturing hood of a size and type in common use and quantify the effect a flange has on its capture efficiency and protection efficiency.

1.3 Hypothesis

The null hypothesis is that the protection efficiency and capture efficiency for the hood studied are not affected by air flow through the hood (Q), cross draft velocity (V_{cross}), presence of a flange (Flange), or interactions between Q and V_{cross} or Flange. Conversely the alternative hypothesis is that for the hood studied the protection efficiency and capture efficiency are affected by one or more of the independent variables (Q, V_{cross} , interactions between Q and V_{cross} or Flange).

It should be noted that cross draft velocities and capturing hood airflows were controlled by adjusting to a set of specific and predetermined fan speeds. The values of V_{cross} were estimated from previous Pitot traverses of the wind tunnel fan inlet duct and were not measured during this study. Hence, V_{cross} was not a random variable but a fix variable with 2 specific values. On the other hand, the capturing hood fan speed was adjusted to 3 specific values during the study; the actual values of Q for the hood were determined by performing Pitot traverses of the duct connected to the hood. Hence, Q varied within 3 distinct and widely separated ranges. Thus Q was given a nominal value equal to the average observed Q at each level of $\text{Freq}_{\text{Hoodfan}}$ (Q_{nom}). The Q_{nom} value allows Q to be treated as a fixed variable.

Hypothesis Model

$$Y = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \varepsilon_{ijkl}$$

Where:

- α = Effect of Q_{nom}
- β = Effect of $\text{Rotate}_{\text{WTfan}}$ or V_{cross}
- γ = Effect of Flange
- $\alpha\beta$ = Effect of Interaction between Q_{nom} and $\text{Rotate}_{\text{WTfan}}$
- $\alpha\gamma$ = Effect of Interaction between Q_{nom} and Flange

$$Y = C_{\text{mouth}}$$

$$H_{0-1}: \alpha_i = 0 \text{ for } i = 1, 2, 3$$

$$H_{a-1}: \text{any } \alpha_i \neq 0$$

$$H_{0-2}: \beta_1 = \beta_2 = 0$$

$$H_{a-2}: \beta_1 \text{ or } \beta_2 \neq 0$$

$$H_{0-3}: \gamma_1 \text{ or } \gamma_2 = 0$$

$$H_{a-3}: \gamma_1 \text{ or } \gamma_2 \neq 0$$

$$H_{0-4}: \alpha\beta_{ij} = 0 \text{ for all } ij$$

$$H_{a-4}: \text{any } \alpha\beta_{ij} \neq 0$$

$$H_{0-5}: \alpha\gamma_{ij} = 0 \text{ for all } ij$$

$$H_{a-5}: \text{any } \alpha\gamma_{ij} \neq 0$$

$$Y = \eta_{\text{e-duct100\%}} \text{ and } \eta_{\text{e-G}}$$

$$H_{0-1}: \alpha_i = 0 \text{ for } i = 1, 2, 3$$

$$H_{a-1}: \text{any } \alpha_i \neq 0$$

$$H_{0-2}: \beta_1 = \beta_2 = 0$$

$$H_{a-2}: \beta_1 \text{ or } \beta_2 \neq 0$$

$$H_{0-3}: \gamma_1 \text{ or } \gamma_2 = 0$$

$$H_{a-3}: \gamma_1 \text{ or } \gamma_2 \neq 0$$

$$H_{0-4}: \alpha\beta_{ij} = 0 \text{ for all } ij$$

$$H_{a-4}: \text{any } \alpha\beta_{ij} \neq 0$$

$$H_{0-5}: \alpha\gamma_{ij} = 0 \text{ for all } ij$$

$$H_{a-5}: \text{any } \alpha\gamma_{ij} \neq 0$$

CHAPTER 2: LITERATURE REVIEW

A review of published scientific literature pertaining to capturing hoods with emphasis on capture efficiency was performed. The following paragraphs will discuss past studies which utilized centerline velocities, velocities fields in front of hoods, capture envelopes, and hood effectiveness.

2.1. Centerline Velocity, Capture Envelopes

DallaValle (1930) defined velocity contour lines in front of capturing hoods. Since then, studies which measured or predicted the centerline velocity and velocities in front of capturing hoods have prevailed in literature (Silverman, 1942; Fletcher B. , 1977; Fletcher B. , 1978; Garrison, 1981; Fletcher & Johson, 1982; Flynn & Ellenbecker, 1987; Conroy, Ellenbecker, & Flynn, 1988). Unfortunately, these investigators developed models that only applied to predicting values of V_x for ideal conditions.

Advances in technology have more recently allowed investigators to make more accurate, more precise, and faster air velocity measurements than in the past. Previously researchers were limited to measuring velocities with single-direction, single point velocity devices. The development of particle image velocimetry (PIV), laser Doppler, omni-directional anemometry, and 3D constant temperature anemometry have allowed investigators to measure air movement in ways which were previously impossible. The later techniques (laser Doppler, omni-directional anemometry, and 3D constant temperature anemometry) are all bound to measuring velocities at a single point. On the other hand, PIV has allowed investigators to simultaneously measure the air velocities induced by the hood and the velocities of competing air currents in any plane in front of a hood.

The use of the PIV system allowed investigators such as Huang *et al.* (2001) to measure the capture envelope of various capturing hoods in less than ideal conditions (i.e. competing air currents, such as cross drafts). However, Huang *et al.* (2001) states the equations developed from the PIV data are reasonable for quick computations to determine the effective capture zone but cannot be used to determine the capture efficiency of the hood.

2.2. Effect of Flanges

DallaValle (1930) proposed that the flange size for capturing hoods should be approximately 5 inches for hoods with a face area of 3 ft². Silverman (1942) suggested that the optimum flange width should be stated in terms of the hood face area. Alden and Kane (1982) later stated that the flange should be such that it intercepts the 5% velocity contour of an equivalent unflanged hood, as computed below.

$$W = 0.75A^{1/2} \quad 2-1$$

Where: W = Flange width
 A = Area of hood face

Fletcher (1978) measured the centerline velocities for hoods having varying flange sizes. He found that increasing the flange size reaches diminishing returns for increasing the velocity measured in front of the hood. The flange size when diminishing returns are reached was found to be equal to the square root of the hood face area:

$$W = A^{1/2} \quad 2-2$$

Where: W = Flange width
 A = Area of hood face

According to Fletcher (1978) adding a flange to a free standing LEV rectangular exhaust hood increases velocities by 33% up to a distance of $X/A^{1/2}$.

$$Q = C_{cap}V(10X^2 + A) \quad 2-3$$

Where: C_{cap} = 1.0 for non-flanged and 0.75 for flanged hoods
 Q = Calculated volumetric flow
 V = Capture velocity, fpm, at distance X
 X = Distance from hood face to farthest point of
 contamination release, Ft.
 A = Hood face area, ft²

In the calculation of required air flow for a rectangular hood, adding a flange decreases C_{cap} from 1.0 to 0.75, thereby reducing the recommended airflow by 25%. This recommendation is consistent with Fletcher (1978) and Dalla Valle (1930).

Equation 2-3 can be solved for V_x :

$$V_x = \frac{Q}{C_{cap}(10X^2 + A)} \quad 2-4$$

If Q is held constant and $C_{cap} = 0.75$ is used for a flange, then V_x increases by 33%, consistent with Fletcher (1978) and Dalla Valle (1930).

2.3. Efficiency

Equations for determining capture efficiency were proposed by Ellenbecker, Gampel, and Burgess (1983). The hypothesis was that through releasing a contaminant at a known rate and measuring the amount collected or not collected by the LEV system one could determine the capture efficiency. Ellenbecker, Gampel, and Burgess (1983) initially proposed Equation 1-1 as a calculation for capture efficiency.

Flynn and Ellenbecker (1986) used sulfur hexafluoride (SF_6) as a tracer gas to evaluate the capture efficiency of flanged capturing hoods under varied cross-drafts, flows, hood diameters, and source distance from the hood face to determine the critical distance for capture of a contaminant into the hood. In this study Flynn and Ellenbecker used the ratio of concentrations of tracer gas measured in the exhaust duct when the source was at the face of the hood (C_z) compared to when the source was placed at varied distances in front of the hood (C_f), to a maximum distance in front of the hood of 1.5 times the duct diameter.

$$n_e = \frac{C_z}{C_f} \quad 2-5$$

Where: n_e = Capture efficiency of the hood
 C_z = Tracer gas concentration measured in the duct downstream of the hood face when the source is a distance of Z from the hood face
 C_f = Tracer gas concentration measured in the duct downstream of the hood face when the source is at the hood face

Flynn and Ellenbecker (1986) found capture efficiency to be highly related to the distance between the hood face and source, the air flow through the hood, and the cross drafts. However, their experiments were conducted at low air flows, 35-140 cfm, with hoods ranging from 2-6 inches in diameter. The range of air flows tested by Flynn and Ellenbecker were well below the range tested in this study. Thus, it would be difficult to compare this study to Flynn and Ellenbecker's study. The studies present in this text range from 380-1100 cfm and were selected to reasonably represent local exhaust ventilation systems used in industry.

2.4. Summary

There is no clear evidence that capture velocities are an acceptable surrogate for capture efficiency or protection effectiveness, yet current guidelines are based solely on velocity measurements to judge hood performance. Little is known about the capture efficiency or protection efficiency of capturing hoods and even less is known about the effect of a flange on the capture efficiency or protection efficiency of a capturing hood. This study will contribute to current information known about capture efficiency, protection efficiency, and the relationship between capture velocity and capture efficiency for a particular small rectangular capturing hood.

CHAPTER 3: APPARATUS

The following is a description of the apparatus used to investigate the hood effectiveness and protection efficiency of the test hood for varied flange, Q , and cross draft velocity conditions.

3.1 Wind Tunnel

The wind tunnel is located in the “High Bay laboratory” (room 157A) located in West Virginia University’s Mineral Resources building. The wind tunnel’s dimensions are shown in Figure 3-1. The wind tunnel is divided into three chambers: the mixing, experimental, and plenum chambers. A bank of HEPA filters backed with activated charcoal are located at the inlet to the wind tunnel and between the experimental and plenum chamber.

Figure 3-1. Interior lay out of the wind tunnel

The interior is finished with dry wall on the walls and ceiling, and linoleum covers the floor. The floor is insulated with Styrofoam™ to reduce heat conduction from the cement floor. The wind tunnel has three entrances which are thirty-two inches by eighty inches. Two entrances provide access to the main “experimental area” of the wind tunnel and the other provides access to the plenum of the wind tunnel. Each entrance is fitted with two double paneled glass storm doors, with one on the interior and one exterior side of the wall. The wind tunnel has two sealed Plexiglass® windows on either side of the experimental chamber’s exterior walls. One is approximately 44 inches by 26 inches and the other is approximately 44 inches by 56 inches.

3.2 Wind Tunnel Cross Draft and Control System

Cross drafts through the wind tunnel are induced by a type BCV-SW size 270 large-capacity industrial fan manufactured by Twin-City Fan and Blower Minneapolis, MN. The flow of the cross draft is towards the manikin's back and the face of the capturing hood. The fan is located above the wind tunnel on a steel platform (see Figure 3-1). The fan's speed is controlled by a Baldor Series 15-H inverter and digital control mounted at eye level on the exterior of the wind tunnel on the plenum end. The wind tunnel fan speed ($Rotate_{WTfan}$) is adjustable in increments of 30 rpms with a range of 0 to 1,560 RPMs. Lewis (2010) found that the $Rotate_{WTfan}$ has a linear relationship to the V_{cross} based on previous Pitot traverses of the inlet duct for the wind tunnel fan:

$$V_{cross} = 0.0637(WTrpm) \quad 3-1$$

Where: V_{cross} = Cross draft velocity
 $Rotate_{WTfan}$ = Speed of the wind tunnel fan

3.3 Capture Hood and Control System

This study utilizes one rectangular capturing hood. For some tests a flange was attached to the capturing hood (see Figure 3-4) and for others it is not (see Figure 3-3). The hood was manufactured by Nordfab Systems, Inc. (Thomasville, North Carolina) and sold as a router hood (Model No. 3231-04). The flange is custom made of Plexiglass® and was designed to be easily attached and detached from the hood.

Figure 3-2. Capturing hood dimensions side view

Figure 3-3. Capturing hood dimensions top view

Figure 3-4. Dimensions of flanged capturing hood

The rectangular capturing hood face is 6 inches vertically by 12 inches horizontally (see Figure 3-3). The hood tapers at a 21° horizontally at the sides and 7.7° vertically at the bottom (see Figure 3-2) to a 4 inch in diameter circular rolled steel duct. The flange is made of 3/8" Plexiglass® and has an approximate width equivalent to the square root of the area of the face, 8.66 inches (see Figure 3-4).

The capturing hood is held 3.5 inches above a table (see Figure 3-5) and is supported by a custom made duct stand. The face of the hood is 14.25 inches from the leading edge of the table and 11 inches from the furthest edge of the source. All dimensions of the hood in relation to the table are shown in Figure 3-5 and Figure 3-6.

Figure 3-5. Front view of the capturing hood and table dimensions

Figure 3-6. Side view of the capturing hood and table dimensions

Air flow through the capturing hood is induced by a 200 volt three-phase BCN-SW industrial fan (Model 250 APP4 CL.L) manufactured by TCF Aerovent Company in Brookings, South Dakota. The industrial fan is controlled by a Teco N3 Inverter with a digital control that is mounted at eye level on the exterior of the wind tunnel plenum. The digital controller allows the user to adjust the electrical frequency driving the fan motor in 0.01 Hz increments.

3.3.1 Air Flow Measurements

The capturing hood is connected to the industrial fan by a system of 8 inch and 4 inch diameter circular rolled steel ducts. The 8 inch ducts are connected to a 4 inch diameter circular duct with a taper. Hood face velocities are determined by two perpendicular ten point Pitot-tube traverse readings conducted according to recommendations in appendix C of the ACGIH's Industrial Ventilation manual. Velocity pressure and static pressure readings are taken using a PVM-100 micromanometer (TSI Inc. Shoreview, MN) which is calibrated with a Dwyer Hook Gauge (model 1425). Data from the micromanometer is electronically captured by a desktop computer using a RS-232 cable through the use of a commercial software program HvMeasurement (Guffey, Morgantown, WV).

The software calculates the average velocity in the duct from the 20 individual Pitot-traverse readings (see Equation 3-2). Using the measured average duct velocity, the average air flow through the duct (Q) is calculated (see Equation 3-4).

$$\bar{V}_{duct} = \frac{1}{20} \sum_{i=1}^{20} \sqrt{\frac{VP_i}{df}} \quad 3-2$$

Where: VP = Velocity pressure measured by a Pitot tube
 $\bar{V}_{duct}$ = Average velocity in duct

$$df = \left(\frac{SP_{duct} + SP_{atm}}{SP_{std}} \right) \left(\frac{T_{duct}}{T_{std}} \right) \left(\frac{\rho_{air}}{\rho_{std}} \right) \quad 3-4$$

Where:

- SP_{duct} = Static pressure of duct
- SP_{atm} = Static pressure of atmosphere
- SP_{std} = Standard static pressure
- T_{duct} = Temperature of duct
- T_{std} = Standard temperature
- ρ_{air} = Density of air
- ρ_{std} = Standard density of air

$$\bar{Q} = \bar{V}_{duct} A_{duct} \quad 3-5$$

Where:

- Q = Average air flow through the duct, cfm
- $\bar{V}_{duct}$ = Average air velocity in the face of the hood, fpm
- A_{duct} = Area of duct (πr^2), ft^2

In order to reduce errors associated with Pitot-tube traverse measurements, two fixed traverse tools (Guffey S. E., 1993) held two Pitot-tubes perpendicular to the duct and at the desired insertion depth, thereby minimizing human error associated with attempting to hold the Pitot tubes in place by hand (see Figure 3-7).

Figure 3-7. Pitot traverse tool

3.4 Experimental Manikin

This study used a heated anthropometrically-scaled manikin (see Figure 3-8). The manikin's dimensions are shown in Table 3-1.

Table 3-1. Anthropometrically-scaled manikin dimensions

Description of Measured Location	Dimensions (inches)
Stature	66"
Eye height	58"
Shoulder height	52.5"
Elbow height	40"
Fingertip height	23.5"
Shoulder breadth	14"
Head length	7"
Head Breadth	6"

The manikin was heated by two 6 meter in length fifty watt flexible heat ropes and one 4.3 meter in length twenty-five watt flexible heat rope, all manufactured by Big Apple Herpetological, Inc. (Hauppauge, NY). The temperature of the flexible heat ropes was controlled by a digital thermostat (BAH-100DC) manufactured by Big Apple Herpetology, Inc. (Hauppauge, NY) to prevent overheating. The flexible heat ropes were inserted into the manikin's head, torso, arms, thighs, and chest cavity (see Figure 3-9). The manikin's arms were heated to the wrists and the legs were heated down to the thighs. Insulation was utilized in the extremities

and core of the manikin to prevent hot spots. The manikin required an approximate warm-up time of 90 minutes to reach final operating temperatures. The power usage of the manikin was continuously metered by a Kill-A-Watt™ power meter (Model P4400 Manufactured by the P4 International Corporation) and periodically checked to ensure consistent power consumption.

Figure 3-8. Manikin

Figure 3-9. Manikin heating system

The experimental manikin was positioned so that its navel was two inches from the leading edge of the table. The medial axis of the manikin was aligned with the center line of the hood and tracer gas source using a laser level. The manikin was fitted with two thermocouples located on the shoulder and mid-back to continuously monitor the manikin's temperature. Thermocouples were calibrated against an American Society of Testing and Materials (ASTM), National Institute Standards and Technology (NIST) traceable laboratory thermometer.

3.5 Breathing System

Human breathing was simulated by a bellows system. This system was used in previous studies (Lewis, 2010; He, 2010; El-Sotouhy, 2008). The bellow system operates at 38 cycles per minute, which is considerably higher than the average adult breathing rate of 12-18 breaths per minute (Tortora & Anagnostakos, 1990). However due to the design of the breathing system a higher breathing rate is required for the system to operate optimally and to produce an at rest minute

ventilation rate approximate to that of an adult at rest. The breathing system produced a measured minute ventilation volume of 976 in³, which is modestly higher than the average at rest minute ventilation rate for an adult of 366-732 in³ but much less than the average found during exercise of 4,271-5,492 in³ (Karwowski & Marras, 1999).

Figure 3-10. Bellows type manikin breathing system

The breathing system draws ambient air in and out of the nostrils of the manikin in a sinusoidal pattern. Air is drawn through plastic tubing ran from the bellows system through the heated chest of the manikin to two 0.25-inch inside-diameter tubes that terminated at the nostrils of the manikin. The two 0.25 inch tubes connect to a single piece 0.5 inch inside-diameter Tygon[®] tubing by way of a plastic Y coupler. The Tygon[®] tubing from the manikin is connected to a 1 inch copper pipe from the bellows system. The copper pipe runs from the exterior of the wind tunnel where the bellows system is located through the wind tunnel wall and connects to the 0.5 inch plastic tubing inside the experimental chamber.

3.6 Tracer Gas Sampling System

Air samples were drawn through 0.125-inch inner diameter hard-plastic tubing and 0.25-inch inside-diameter Tygon® tubing by SKC Inc. model 222 and SKC Inc. pocket pump air sampling pumps at a flow rate of 0.2 lpm. Samples taken inside the wind tunnel were routed through the wall of the wind tunnel through compression fittings. Sample lines were color coded on each side of the wind tunnel wall to identify sample locations. Samples were taken simultaneously by drawing air into Tedlar® bags through different trains of tubing, pumps, and bags from the locations listed in Table 3-2.

Table 3-2. Tracer gas sample locations

Location	Abbreviation	Description
Manikin's nose	C_{nose}	0.5 cm laterally from nasal orifice
Manikin's mouth	C_{mouth}	At the mouth 3 cm from the right of the lip
Inside duct downstream of hood face	C_{duct}	Approximately 5 m downstream of the hood before the duct passes through the side of the wind tunnel wall
Wind tunnel inlet	C_{ambient}	2 m in front of the inlet of the wind tunnel

Samples were collected in Tedlar® bags using SKC Inc. air sampling pumps to achieve an approximate total sample volume of 4 liters over the test period of approximately 20 minutes. The bag samples were analyzed using a Gaset model DX 4015 Fourier transform infrared (FT-IR) spectrophotometer to determine the concentration of Freon 134a in each collection bag. The concentration of Freon 134a in each bag reflected the average concentration of the sampling location over the experimental period for that location.

Samples within the duct were taken approximately 17' (5 meters) downstream and two elbows downstream of the hood (see Figure 3-11). According to Hampl, Niemela, Shulman, & Bartley (1986) in order to obtain an accurate sample when performing tracer gas testing of industrial exhaust systems, one should sample at a duct location at least 4 duct diameters downstream of the last elbow for systems with two elbows.

Figure 3-11. C_{duct} sample location

Samples lines and pumps were tested for leaks and tracer gas adsorption prior to the study. This was done by attaching a 10-liter Tedlar® bag with a known concentration of Freon 134a at the start of the sample train being tested. The Freon 134a mixture passed through the sample train and was collected in a clean 10-liter Tedlar® bag on the exterior to the wind tunnel. The two bags were analyzed by the FTIR and compared to determine the integrity of the sample system. Through this method no leaks in the sampling system were found.

3.7 Tracer Gas Measurement System

Samples were analyzed using a Fourier Transform Infrared (FT-IR) analyzer (see Figure 3-12) manufactured by Gasmeter (model DX-4015). The FT-IR was calibrated using known Freon 134a concentrations at 0 to 200 PPM. Known concentrations were created by adding 3 liters of ambient air to a 5 liter sample bag using a 3 liter gas-tight syringe manufactured by Pulmonary Data Service Instrumentation. Next, a known amount of Freon 134a was injected into the same sample bag using a gas-tight syringe manufactured by the Hamilton Company.

Prior to analysis, the FTIR was given at least 30 minutes to reach operating temperature. Following the warm-up period the sample cell of the FTIR was purged with nitrogen for 5 minutes, followed by a 5 minute resting period while the background was established by the instrument's software.

Sample bags are connected to the FTIR using ¼" plastic tubing and plastic friction couplers. The FTIR analysis was controlled by the Calcmeter software version 10.09 (Gasmeter Technologies Oy, Helsinki, Finland). The sample was drawn into the FTIR for 1 minute and analyzed for 1 minute prior to recording the results. Results were recorded by hand as well as automatically logged to a computer file by the Calcmeter software. The "residual" for each sample were also recorded, along with any warnings or errors the software associated with the sample. The "residual" given by the Calcmeter software is a measure of how similar the sample absorbance spectra is to the reference absorbance spectra for the chemical of interest, a value greater than 0.01 is given a "warning" code and 0.02 is given an "error" code by the software. Samples which return a warning are considered to be acceptable and samples which return an error were discarded and the test was repeated.

Figure 3-12. Gasmeter FT-IR, gas analysis system

To reduce high residual values and the occurrence of errors or warnings in the analyzed samples, the samples taken at C_{duct} were diluted to a lower concentration. The ratio of dilution depended on the hood fan speed since duct concentrations were higher for lower airflows. The samples taken with a hood fan controller frequency of 23 Hz were diluted 6:1 and the samples taken at a hood fan controller frequency of 40 and 55 Hz were diluted 3:1. Both the diluted and undiluted samples were analyzed by the FTIR.

Data from the Pitot traverses and from the FTIR were logged in HvMeasurement for analysis.

3.8 Tracer Gas Release and Metering System

The tracer gas mixture used in this study was a mixture of ultra-high purity helium and Freon R-134a, both manufactured by Airgas, Inc. Both helium and Freon flowed from their respective cylinders to their respective pressure regulators, which reduced the internal pressure to 15 PSI (see Figure 3-13). Each gas was fed to a factory calibrated gas specific mass flow controller (Model GFC-10, Manufactured by Aalborg Instruments and Controls, Inc.) by way of 0.25 inch internal diameter Tygon® tubing. Helium was released at a rate of 4.9 liters per minute (lpm) and Freon was released at 1.79 lpm.

Figure 3-13. Flow diagram of tracer gas mixture

The flow rate of gas from the mass flow controller was calibrated using a Bios Defender 510 primary flow standard (Bios International Corporation of Butler, NJ) after allowing the mass flow controller to warm-up for at least 30 minutes and gas to flow for at least 5 minutes prior to calibration. Calibration was performed before and after the experiment.

Figure 3-14. Tracer gas mixture delivery controls

Figure 3-15. Tracer gas mixture release locations

Gas from each mass flow controller is mixed into a single line by a Y-connection. The tracer gas mixture is split again by another Y-connection where two valves control the direction the tracer gas mixture by opening one valve while keeping the other shut (see Figure 3-13 and Figure

3-14). The tracer gas mixture was directed to either the duct or the source by manipulating the valves (see Figure 3-15). The density of the mixture was modestly less dense than air, at 1.145 g/l.

The source was a rectangular box constructed of 0.1875 inch Plexiglass® (see Figure 3-16) with approximate external dimensions of 1.375 inches in height, 1.375 inches in depth and 12.375 inches in length. The approximate internal dimensions were 1 inch in height, 1 inch in depth, and 12 inches in length. The midpoint of the source was aligned with the center line of the capturing hood using a laser level.

Figure 3-16. Tracer gas source

The tracer gas mixture enters by way of four 1/8 inch plastic tubes routed through the bottom of the table and into four compression fittings mounted in the bottom panel of the rectangular source. The interior of the source was filled with three layers of 3M Scotch Bright™ porous material to ensure even dispersion of the tracer gas mixture through the interior of the source. The top of the source contained three rows of 3/16 inch holes. Two rows had 30 holes and one had 31 holes, for a total of 91 holes. Each row was spaced at 0.5 inches from the next row and 0.375 inches between each hole in a row. The tracer gas mixture exited the source with a calculated bulk velocity of 0.02 fpm and an average velocity through the holes of 13 fpm.

3.9 Point Velocity Measurement System

The velocities induced by the hood (V_x) at the source location (see Figure 3-17) were measured using a constant temperature anemometer (CTA) (Model 54T30, Dantec Dynamics A/S Skovlunde, Denmark) equipped with a model 55P16 single sensor hot wire miniature probe (see Figure 3-18).

CTA probe is on
the same plane
as source

Figure 3-17. V_x measurement location with CTA

Figure 3-18. Detailed description of CTA probe used with permission by Dantec Dynamics.

Analog voltages from the CTA were acquired by a National Instruments data acquisition system and converted to digital voltage signals. The National Instruments data acquisition system includes a BNC module (Model NI9215), a module carriage (Model NI_cDAQ 9172), and National Instrument's Signal express data acquisition software at sample rate set at 1 KHz for during calibration and 100 Hz during the study.

Figure 3-19. CTA principle of operation used with permission by Dantec Dynamics

To measure values of V_x the CTA probe was positioned at the leading edge of the source, 11 inches from the hood's face, on the midpoint and centerline of the hood face, 6.5 inches above the table. This measurement technique is constant with recommendations for the evaluation of capturing hoods given by the Industrial Ventilation Manual (ACGIH, 2007). Positioning was verified through the use of a laser level. Fan controller frequencies of 23, 40, and 55 Hz were chosen to produce an approximate V_x of 50, 100, and 150 fpm, respectively.

The CTA and probe were calibrated using a TSI, Inc. Model 1125 calibrator (see Figure 3-20) designed for calibrating CTAs and other hot wire anemometers. The probe was positioned into the calibration chamber so that the probe's wire was perpendicular to the flow. Laboratory air was connected to the calibrator by $\frac{1}{4}$ inch plastic tubing. Flow through the calibrator was controlled by a needle valve. Static pressure measurements from the low velocity calibration chamber were taken using the PVM-100 micromanometer. Velocity through the chamber was calculated from static pressure measurements on the assumption of no losses. The CTA was calibrated to velocities from 0 to 200 fpm, the calibration is detailed in Appendix II.

Figure 3-20. TSI, Inc. 1125 calibrator

3.10 Environmental Measurements

Temperature, humidity, and barometric pressure were taken prior to each test, recorded, and inputted into the HvMeasurement software, which used them to compute air densities (see Equation 3-4).

Figure 3-21. Psychrometer

Temperature measurements from the wind tunnel's walls are taken using an Infrared thermometer and thermocouples. Wet and dry bulb thermometer readings were measured

using a psychrometer (Environmental Tectonics Corporation, South Hampton, PA) taken from inside the wind tunnel prior to each test(see Figure 3-21). All thermometers were checked against an ASTM laboratory thermometer (Ertco, Sn: 8859) by comparing temperature readings simultaneously in the same environment. Barometric pressures were taken at the outer wall of the wind tunnel using a standard laboratory mercury barometer (Environmental Tectonics Corporation, South Hampton, PA).

CHAPTER 4: METHODS

4.1 Study Design

The dependent variables that were measured in this study are the concentrations of Freon 134a at the nose, mouth, and duct (C_{nose} , C_{mouth} , and C_{duct}).

Figure 4-1. Prototypical capturing hood

Figure 4-2. Prototypical flanged hood

The independent variables were the presence of a flange (Flange), the average observed air flow (Q_{nom}) through the hood at three levels of capturing hood controller speeds ($\text{Freq}_{\text{HoodFan}}$), and the estimated wind tunnel cross draft (V_{cross}) at two levels of wind tunnel fan rpm ($\text{Rotate}_{\text{WTfan}}$). The capturing hood fan controller was set to three levels 23, 40, 55 Hz such that the flow through the hood produced a V_x of approximately 50, 100, and 150 feet per minute. The wind tunnel fan was set to an rpm of 150 and 930 such that the calculated V_{cross} was approximately 10 and 60 feet per minute. Furthermore, there was an expected interactive effect between V_{cross} and Q due to the innate characteristics of the wind tunnel, and an interactive effect between Q and Flange on the dependent variable.

This study was divided into four parts, three preliminary studies and one main study. The preliminary studies were: velocity measurements at V_x , establishing the 100% duct concentration when tracer gas is released directly into the duct, and discussion and analysis of interactive effects on Q . The main study is where the capture efficiency and protection efficiency for the test hood are determined. Each part of this study used a randomized factorial design.

4.1.1 Preliminary Study One

For the first preliminary study, velocity measurements at V_x , all experimental conditions were tested, $Freq_{HoodFan}$, V_{cross} , and Flange (see Table 4-1). Each condition was replicated twice resulting in 24 tests which were conducted in a single randomized order. This preliminary study had the following goals:

1. Determine whether V_x is significantly affected by changes in Q , the presence of a flange and levels of V_{cross}
2. Measure V_x for each condition
3. Determine how well the “design” equations presented in ACGIH IVM predict V_x

Table 4-1. Experimental Conditions for preliminary study one and the main study

Treatment	Flange	$Freq_{HoodFan}$	V_{cross}
1	Yes	23	10
2	Yes	23	60
3	Yes	40	10
4	Yes	40	60
5	Yes	55	10
6	Yes	55	60
7	No	23	10
8	No	23	60
9	No	40	10
10	No	40	60
11	No	55	10
12	No	55	60

4.1.2 Preliminary Study Two

The second preliminary study, establishing the 100% duct concentration, tested only those conditions which have an effect on the concentration of tracer gas in the duct, $Freq_{HoodFan}$ and $Rotate_{WTFan}$ (see Table 4-2). This was done to allow computation of capture efficiency (which can be computed as $C_{duct}/C_{duct-100\%}$, Equation 1-3) in the main study by measuring the concentration of Freon in the duct when 100% capture was assured ($C_{duct100\%}$). The 6 conditions were replicated twice resulting in 12 tests which were conducted in a single randomized order.

In addition to these 12 tests, on each day of the main study two 100% capture tests were performed. The two 100% capture tests were selected at random and randomly placed into the block of main study test for that day.

Table 4-2. Conditions for testing 100% capture

Treatment	Freq_{HoodFan}	V_{cross}
1	23	10
2	23	60
3	40	10
4	40	60
5	55	10
6	55	60

4.1.3 Preliminary Study Three

The third preliminary study analyzes and discusses the individual and combined effects of the two fan controller settings of Rotate_{WTfan} and Freq_{HoodFan} on the observed Q values. This study used data from both preliminary study number two and the main study. It is known that the Rotate_{WTfan}, which controls the cross draft through the wind tunnel, creates a negative pressure inside the wind tunnel; the negative pressure is greater at higher levels. This negative pressure inside the wind tunnel reduces the observed air flow through the capturing hood fan (Q). Since Q is a usefully measure in this study and desired for statistical analysis it is important to understand the degree of dependence or independence of Q on Rotate_{WTfan} and Freq_{HoodFan}. No additional data was collected for this preliminary study.

4.1.4 Main Study

The main study included a total of 24 tests, including 2 replications for each of the 12 conditions (see Table 4-1). The 24 tests were randomized in one single order and broken into 4 blocks of 6 tests; each block was conducted in one day. Testing occurred over 4 days, including 6 main study tests each day and two preliminary 100% capture study tests each day. The statistical power of the study was not determined prior to collecting data, but this study was modeled on previous tracer gas studies where two replications provided sufficient power (El-Sotouhy, 2008; He, 2010).

The data was analyzed for statistical significance using multiple regression analysis and a fixed-effect ANOVA model in the Data Desk software (Data Descriptions, Cornell, NY).

4.2 Procedure

The following are the procedures used to conduct the preliminary V_x study, preliminary 100% duct study and the main study.

4.2.1 Calibrations prior to testing

1. Calibrate the FT-IR with known concentration of Freon ranging from 0 – 200 PPM
2. Calibrate Mass Flow Controllers using the DryCal
3. Calibrate the microanemometer using Dwyer hook gauge
4. Calibrate thermocouples and thermometers using ASTM thermometer

4.2.2 Preliminary study one: Measurement of V_x

1. Calibrate the CTA using the TSI model 1125 calibrator
 - a. Connect CTA to the 12 volt battery
 - b. Connect BNC cables to the probe and data acquisition system
 - c. Place probe into the smaller barrel of the “unit 2” on the calibrator
 - d. Orient the probe such that the probe’s wire is perpendicular to the air flow
 - e. Open National Instrument’s Signal Express data acquisition program
 - f. Attach the PVM-100 micromanometer to the static pressure port on “unit 2” of the calibrator.
 - g. Attach laboratory air supply to the calibrator and turn on lab air
 - h. Record temperature and pressure
 - i. Adjust the flow valve on the calibrator to achieve the desired velocity pressure in “unit 2” of the calibrator
 - j. Acquire CTA voltages at 1k Hz for 1 second
 - k. Record the average voltages for the sample period
 - l. Repeat for the desired range of velocities to be measured
 - m. Graph in excel and record polynomial calibration equation
 - n. Apply the polynomial calibration equation to the equation in the signal express program
 - o. Remove the CTA probe from the calibrator
2. Position the CTA probe on the centerline of the hood at the furthest point of the source (V_x) {distance of 11 inches from hood face and 6.5 inches above the table}
3. Orient the probe’s wire such that it is perpendicular to the flow of air (hood face)
4. Verify positioning with a laser level and reposition if needed
5. Record environmental data and all necessary information of the experiment’s data sheet

6. Shut wind tunnel doors
7. Turn capturing hood on and adjust to desired controller frequency
8. Turn wind tunnel fan and adjust to desired fan rpm
9. Allow room to stabilize for 5 minutes
10. Set the signal express program to data log
11. Acquire CTA voltages at 100 Hz for 600 seconds (10 minutes)
12. Measure flow through the capturing hood by Pitot traverse
13. Repeat twice for all experimental conditions in random order

4.2.3 Preliminary study two: Measurement of 100% duct

1. Uses same procedures as the main study with following exceptions:
 - a. The condition flange is not used
 - b. Only bag samples from the duct and ambient location are taken

4.2.4 Main study

4.2.4.1 Prior to each day to testing

1. Manikin heat turned on at least 1.5 hours prior to experiment
2. Plug in mass flow controllers at least one hour prior to experiment
3. Turn on FTIR at least one-half hour prior to experiment.
4. After FTIR has been running for at least one-half hour purge the FTIR with ultra-high purity nitrogen for five minutes
5. Stop purging of FTIR and wait five more minutes
6. Run the background on the FTIR
7. Purge Tedlar™ sampling bags twice with ambient air
8. Check manikin posture, location of its head in the plane of the hood face, locations of hands to each side of the source, heating and breathing

4.2.4.2 Prior to each test

1. Turn on wind tunnel fan and exhaust hood fan and adjust the fan controllers to desired airflows
2. Turn on the manikin breathing system
3. Turn on sample pumps
4. Connect Tedlar™ bags to the sampling pumps
5. Record environmental conditions in the wind tunnel (temperature, humidity, barometric pressure)
6. If required attach flange
7. Open or close valves on the tracer gas release system to direct tracer gas mixture to the desired location
8. Turn on tracer gas release system

4.2.4.3 Testing procedure

1. Ensure wind tunnel doors are closed
2. Wait 10 minutes with tracer gas running and wind tunnel doors shut for the wind tunnel to equalize
3. After 10 minutes open valves on sampling bags
4. While sample bags are filling conduct Pitot traverses at the capturing hood duct
5. Allow experiment to run for 20 minutes
6. After 20 minutes close valves on sampling bags and disconnect the bags from the pumps

4.2.4.4 After each test

1. For tests where the hood fan frequency was 40 or 55 (23) Hz dilute bags 3:1 (6:1) by:
 - a. Connect duct sample bag to 3 liter syringe
 - b. Open duct sample bag
 - c. Draw ~0.2 liters of the duct sample into 3 liter syringe
 - d. Close duct sample bag
 - e. Disconnect bag from syringe and exhaust syringe into ambient air
 - f. Connect sample bag to syringe and draw 1 liter (0.5 liters) of sample into 3 liter syringe
 - g. Close sample bag and disconnect the syringe
 - h. Connect syringe to a new clean sample bag and open valve
 - i. Add 1 liter (0.5 liters) of duct sample to new sample bag
 - j. Close new sample bag and disconnect syringe
 - k. Draw 3 liters of ambient air into syringe
 - l. Connect syringe to new sample bag and open
 - m. Add 3 liters of air to the new sample bag
 - n. Close new sample bag and disconnect syringe
2. Connect a sample bag to the FTIR and open valve on sample bag
3. Draw sample into the analyzer for 1 min
4. Analyze sample for 1 min and note Feron-134a concentration, residuals, and warnings or alarms on screen
5. Repeat for the next sample bag
6. Rinse analyzed sample bag twice with lab air and lab vacuum prior to reusing bags

CHAPTER 5: PRELIMINARY STUDY ONE

The main study does not use V_x as an independent variable because, as is demonstrated here, it is a function of the hood fan output (Q), the presence of the flange, and, to a much lesser degree, the cross draft velocity (V_{cross}). Hence, using V_x would make it difficult to determine the independent effects of the other variables.

However, since V_x is the basis of current practices in evaluating capture hoods, this study was done to allow estimation of V_x values for the conditions of this study.

This preliminary study measured capture velocities (V_x) at the source for each combination of hood fan setting ($\text{Freq}_{\text{HoodFan}}$), wind tunnel cross draft velocity based on $\text{Rotate}_{\text{WTFan}}$ (V_{cross}), and Flange (present or not). The study determined the velocity at the source (V_x) on the centerline of the hood face without a manikin present. The measurement location and absence of a “worker” are consistent with current recommendations for evaluating capturing hoods in the Industrial Ventilation Manual (ACGIH, 2007).

Specifically, this preliminary study had the following goals:

1. Determine whether V_x is significantly affected by changes in Q , the presence of a flange and levels of V_{cross}
2. Measure V_x for each condition
3. Determine how well the “design” equations presented in ACGIH IVM predict V_x

5.1 Study Design

The study was a randomized factorial design with the same conditions investigated in the main study (see Table 4-1), including air flow through the hood based on 3 levels of $\text{Freq}_{\text{HoodFan}}$ (Q), 2 levels of V_{cross} , 2 levels of Flange (on/off), and with two replications for each combination. Tests of all conditions and replications were conducted in one randomized order.

5.2 Results

As expected, values of V_x increased with increasing Q , V_{cross} , and with Flange (see Table 5-1). The observed velocities at V_x ranged from 37 to 160 fpm without a flange and 73 to 227 fpm with a flange. The range of measured V_x values fell fairly close to the desired range of 50 to 150 fpm. The minimum V_x recommended by the Industrial Ventilation Manual is 100 fpm for the conditions tested. The minimum V_x used in the study about 40 fpm, however as shown in the main study the hood was still highly effective.

Table 5-1. Velocity measurements by CTA at the source on the centerline of the hood (V_x) for each condition

Freq _{HoodFan}	Avg Q, cfm	V_{cross} , fpm	Flange	Mean V_x fpm	V_x StdDev fpm	Flange		No Flange, due to V_{cross}		Flange, due to V_{cross}	
						ΔV_x fpm	% ΔV_x	ΔV_x , fpm	% ΔV_x ,	ΔV_x , fpm	% ΔV_x ,
23	425	10	No	36	8	37	102%				
23	425	10	Yes	73	10			27	75%	5	7%
23	367	60	No	63	17	15	23%				
23	362	60	Yes	78	15						
40	792	10	No	93	14	61	65%				
40	797	10	Yes	154	15			28	30%	11	7%
40	758	60	No	121	21	44	36%				
40	753	60	Yes	165	21						
55	1112	10	No	138	15	73	52%				
55	1120	10	Yes	210	19			24	17%	16	8%
55	1083	60	No	161	20	65	40%				
55	1087	60	Yes	227	21						

On average the Flange added 53% to the measured value of V_x . As shown in Table 5-1, at lower levels of V_{cross} the velocity added to V_x by Flange decreased from 102% to 52% with increasing levels of Q . At higher levels of V_{cross} the velocity added to V_x by Flange increased from 23% to 40% with increasing levels of Q . This effect may be explained by V_{cross} at higher levels reducing the air flow through the hood and adding velocity to the measured V_x . Table 5-3 shows the amount of velocity added to V_x due to the change in V_{cross} when no flange is present, which is

fairly constant at 26 ± 2 fpm. The increasing effect of the flange at the higher level of V_{cross} therefore appears to be the velocity added by the flange overcoming the velocity added by V_{cross} to V_x .

Figure 5-1. V_x Measurements by CTA.

The V_x measurements are all highly linear ($R^2 > 99\%$) with increasing levels of Q . Adding a flange appears to change the relationship between Q and V_x , by increasing the slope. This suggests that a flange's effect on V_x is not simply an additive effect as assumed by the Industrial Ventilation Manual (ACGIH, 2007), but the effect increases as Q increases. V_{cross} appears to have a small effect on slope and the Y-intercept; however the effect is not consistent across all conditions and the Y-intercept it is not simply the difference in V_{cross} .

5.3 Effect of Variables on V_x

Analysis of variance with a fixed-effect model was performed for the effect of Q_{nom} , V_{cross} , Flange, $Q_{\text{nom}} \cdot V_{\text{cross}}$, and $Q_{\text{nom}} \cdot \text{Flange}$ on the measured values of V_x . Only data collected as part of Preliminary Study One was used in this analysis. In ANOVA analysis the average observed Q for

each level of $Freq_{Hoodfan}$ was used in place of the observed Q for each treatment. This was done because the observed Q is shown in Preliminary Study Three to modestly dependent on V_{cross} . The average value of Q is noted as the nominal value of Q for each level of $Freq_{Hoodfan}$ (Q_{nom}).

Table 5-2. Analysis of Variance for dependent variable V_x

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	384605	384605	6313.8	≤ 0.0001
Q_{nom}	2	59171.7	29585.8	485.69	≤ 0.0001
V_{cross}	1	2041.67	2041.67	33.517	≤ 0.0001
Flange	1	14491.4	14491.4	237.9	≤ 0.0001
$Q_{nom} * V_{cross}$	2	21.5098	10.7549	0.17656	0.8399
$Q_{nom} * \text{Flange}$	2	1875.61	937.807	15.395	0.0002
Error	15	913.726	60.9151		
Total	23	78515.6			

$$\text{ANOVA Model: } Y = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \varepsilon_{ijkl}$$

Where:

- Y = Dependent variable V_x
- α = Effect of Q_{nom}
- β = Effect of V_{cross}
- γ = Effect of Flange
- $\alpha\beta$ = Effect of Interaction between Q_{nom} and V_{cross}
- $\alpha\gamma$ = Effect of Interaction between Q_{nom} and Flange

The effect of variables Q_{nom} , V_{cross} , Flange, and the interaction term $Q_{nom} * \text{Flange}$ were found to be highly significant ($p < 0.001$) with V_x . Given the ANOVA model, the variance in V_x is mostly explained by Q_{nom} , which contributes to 75% of the Sum of Squares, while V_{cross} and $Q_{nom} * \text{Flange}$ explained only 3% and 2% of the variance, respectively. These effects are consistent with observations from Figure 5-1. It should be noted that the ANOVA model was a fixed-effect model and may only be applied to the specific levels for each variable tested in this study.

In conclusion, the variables which have an effect on V_x for this study are Q_{nom} , V_{cross} , Flange, and the interaction between Q_{nom} and Flange. V_x was mostly affected by Q_{nom} . If it is true that V_x

predicts protection efficiency or capture efficiency, then one would expect that protection efficiency or capture efficiency to be determined by the same variables.

5.4 Comparison of Measure V_x to V_x Predicted by Equation 2-4

With the results showing a greater than 33% increase in capture velocity due to the addition of a flange as assumed with Equation 2-4 presented in the industrial ventilation manual (ACGIH, 2007), the measured values of V_x were compared to the predicted values of V_x (see Equation 2-4).

Table 5-3. V_x calculated from ACGIH's design formula and measured V_x values.

V_{cross}	Hz	Avg Q cfm	No Flange			Flange		
			Predicted V_x , fpm	Measured V_x , fpm	%Diff.	Predicted V_x , fpm	Measured V_x , fpm	% Diff.
10 fpm	23	425	47.7	36.4	-23.8%	63.7	73.5	15.4%
	40	795	89.3	92.8	4.0%	119.1	153.6	29.0%
	55	1115	125.2	137.6	9.9%	167.0	210.3	26.0%
60 fpm	23	365	41.0	63.1	54.0%	54.7	78.2	43.1%
	40	755	84.8	121.0	42.7%	113.1	164.8	45.7%
	55	1085	121.9	161.2	32.2%	162.5	226.5	39.4%

The errors from between the measured and predicted V_x given by Equation 2-4 were less at V_{cross} of 10 (-24% to 10%) and greater at V_{cross} of 60 fpm (32% to 54%). Clearly values predicted by Equation 2-4 fit experimental values much better when V_{cross} was lower than at a higher V_{cross} . Equation 2-4 also performed poorly when predicting the V_x with the presence of a flange (see Figure 5-2, Figure 5-3, and Figure 5-4).

Figure 5-2. Graph of measured V_x with a cross draft of 10 fpm and the predicted V_x from Equation 2-3 given in ACGIH's IVM.

Figure 5-3. Graph of measured V_x with a cross draft of 60 fpm and the predicted V_x from Equation 2-3 given in ACGIH's IVM.

Figure 5-4. Graph of measured V_x with a cross draft of 10 and 60 fpm and the predicted V_x from Equation 2-3 given in ACGIH's IVM.

Equation 2-3, used to predict V_x , does not include parameters for the presence of a table or a cross draft, which both were present during testing. Since the modifier used in Equation 2-3 for a flange is based on the observed effect of a flange when no table or cross draft was present, it is easy to understand why the equation did not predict V_x accurately. In application the direction and intensity of the cross draft would be highly variable and very difficult to predict.

CHAPTER 6: PRELIMINARY STUDY TWO

Previous experience with the apparatus used in the main study showed that capture efficiencies computed using the reported values from the mass flow controllers often exceeded 100%, which of course violates mass balance and cannot be correct. Despite diligent attempts, it has not been possible to remedy this error.

For that reason, the main study computes capture efficiency in two different ways: (1) using Equation 1-2, which uses the generation rate reported by the mass flow controller (G) and (2) Equation 1-3, which does not use G . Equation 1-3 uses the concentration of Freon in the duct measured when 100% capture was assured. This preliminary study was done to determine the concentrations of Freon in duct that occur when 100% capture is assured ($C_{\text{duct-100\%}}$). The $C_{\text{duct-100\%}}$ values are then used to compute the capture efficiency measure ($\eta_{\text{e-duct100\%}}$) in the main study.

Since 100% capture is assured the capture efficiency based on G ($\eta_{\text{e-G}}$), Equation 1-2, was also calculated to determine the degree to which the equation over estimates the capture efficiency. The measure of $\eta_{\text{e-G}}$ may then be adjusted reflect a maximum average value of 100%.

6.1 Study Design

This preliminary study was a randomized factorial design conducted to establish the Freon concentration in the duct for the situation where 100% capture was assured ($C_{\text{duct-100\%}}$). The independent variables tested were the observed airflow in the duct (Q) for 3 levels of hood fan controller frequency ($\text{Freq}_{\text{HoodFan}}$) and 2 levels of V_{cross} . Each combination of $\text{Freq}_{\text{HoodFan}}$ and V_{cross} was replicated twice in a single random order.

6.2 Apparatus and Methods

With a few exceptions, the apparatus and methods were the same as those described in Chapter 3 and 4. One exception was that only $C_{\text{duct-100\%}}$ and C_{ambient} samples were taken. They were taken while all of the tracer gas mixture was being continuously released directly into the

duct, with none released into the custom made source. The mixture of Freon and helium was the same as in the main study.

For some tests the $C_{\text{duct-100\%}}$ bag samples were mixed with clean air to dilute the bag concentration. This was done to avoid excessively high “residuals,” which were thought to occur most often with in a specific range of concentrations. For that reason, the sampling bag was mixed with 3:1 with air when $\text{Freq}_{\text{HoodFan}} = 40 \text{ Hz}$ or 55 Hz and with 6:1 air when $\text{Freq}_{\text{HoodFan}} = 23\text{Hz}$.

Figure 6-1. Undiluted 100% duct sample results and the corresponding residual value given by the FTIR, error statements were applied at residual >0.02.

Figure 6-2. Diluted 100% duct sample results and the corresponding residual values given by the FTIR, not all values shown are used in data analysis.

As a check, the sampling bag concentrations were analyzed both before and after dilution. As feared, the Gastec software indicated an error due to excessive residuals (i.e., >0.02) for all undiluted samples except those measured when $\text{Freq}_{\text{HoodFan}} = 23 \text{ Hz}$, see Figure 6-1. In those cases only the diluted sample results were used in further analyses. Fortunately, no excessive residuals were reported for the diluted samples, see Figure 6-2. Thus for later analyses, undiluted sample results were used for samples where $\text{Freq}_{\text{HoodFan}} = 23 \text{ Hz}$ and diluted sample results were used for $\text{Freq}_{\text{HoodFan}} = 40$ and 55 Hz .

6.2 Results

The results are shown in Table 6-1. The capture efficiency values (η_{e-G}) were computed from C_{duct} , G , and Q using Equation 1-2.

Table 6-1. 100% capture study results.

$Freq_{HoodFan}$ Hz	V_{cross} fpm	Q cfm	$C_{duct-100\%}$ ppm	η_{E-G} (%)
23	10	438.3	176.4	121.8
23	10	432.0	150.6	102.2
23	10	421.4	151.9	100.8
23	10	438.8	149.7	103.5
23	10	436.5	144.2	99.2
23	60	366.8	149.0	85.9
23	60	375.6	155.3	91.9
23	60	382.6	171.6	103.4
23	60	373.5	170.4	100.3
Average			157.7	101.0
40	10	794.2	88.4	109.8
40	10	791.1	87.4	108.9
40	10	794.7	98.4	123.2
40	60	763.0	84.8	101.9
40	60	760.3	84.4	100.9
40	60	764.8	92.9	111.7
Average			89.4	109.4
55	10	1112.7	60.1	105.3
55	10	1103.6	61.4	106.6
55	10	1119.0	68.7	121.2
55	10	1111.6	66.7	116.8
55	10	1118.9	54.1	95.2
55	60	1094.4	60.8	104.6
55	60	1094.6	66.6	114.7
55	60	1098.0	67.7	117.0
55	60	1091.7	60.6	104.2
Average			63	109.5

The measured concentration of Freon in the duct decreased exponentially with increasing levels of Q (see Figure 6-3), as expected. One would expect V_{cross} to have no direct effect on $C_{duct-100\%}$. However, higher values of V_{cross} are necessarily associated with higher static pressures inside the wind tunnel, which serves to reduce the airflows produced by the hood fan at any given value of $Freq_{HoodFan}$. As a result, the value of Q is slightly lower when $V_{cross} = 60$ fpm than when $V_{cross} = 10$ fpm. With 100% capture the concentrations should be determined only by the level of Q. Instead, there appears to be small but distinct effect of V_{cross} on values of $C_{duct-100\%}$.

Figure 6-3. Diluted Freon duct samples from the 100% duct tests

Figure 6-4. Unadjusted capturing efficiency for the 100% duct study calculated using Equation 1-2

6.3 Discussion

Figure 6-4 graphs the capture efficiencies as computed by Equation 1-2, for which the numerator has values of $C_{\text{duct-100\%}}$ and the denominator has values of the measured release rate (G) of Freon-134a and Q. This measure is based on mass balance, the true ratio must be unity. Nevertheless, as shown in Figure 6-4, the ratios were in the range of 83-122%, indicating very high variability (0.094) and a mean value of 106.3%.

The observed mean is greater than unity. However, the 90% confidence interval of the mean is 90-122%. Since that range includes unity, one cannot safely dismiss the possibility that the true mean is unity. In short, the coefficient of variation of 9% is high enough that the efficiency here must be considered to be a very imprecise tool but it is not necessarily an inaccurate one.

Investigations to determine the known errors for the elements of the procedure have not revealed the source of this high variability and impossibly high values of capture efficiency. The FTIR calibration showed a high degree of linearity ($R^2 = 99.5\%$, p for slope < 0.0001) and the coefficient of variation for Q for the same conditions was less than 1.6%. The mass flow device that measured and controlled the rate of release of the Freon-134a showed accurate and stable calibrations.

The remaining source of error is error in injecting Freon-134a in the creation of known concentrations for calibrations. However, since the original “calibration” of the unit has not been changed and comparisons to known concentrations of Freon 134a have shown remarkable accuracy and stability.

Table 6-2. Statistics for the Freon concentrations measured during the 100% capture tests

Freq_{HoodFan}	Avg Q cfm	Count	Mean ppm	Median ppm	Variance	StdDev	Range ppm	StdErr
23	407	9	157.66	151.9	139.0	11.79	32.11	3.93
40	778	6	89.38	87.9	28.97	5.38	14.04	2.20
55	1105	9	62.97	61.4	22.82	4.78	14.68	1.60
Overall	762	24	105	87.9	1902.42	43.62	122.28	8.9

6.4 Conclusions

Under perfect conditions the capturing hood should have mean η_{e-G} of 100%. However, the actual mean for η_{e-G} during the 100% capture study was 106.3%. The source of this error is unknown. It is not clear if the results are inaccurate, though they are certainly imprecise. However, since later determinations of efficiency will also show values well in excess of 100%, the analyses in following chapters will assume a constant 6.3% error and adjust for it.

CHAPTER 7: PRELIMINARY STUDY THREE

In regression analyses it is important to know whether independent variables are independent and if not, to what degree they are mutually dependent. In the main study it is useful to consider Q and V_{cross} as independent variables, yet previous results have shown that Q actually varies slightly with changes in V_{cross} due to the higher negative pressures in the wind tunnel associated with higher values of V_{cross} , see Figure 7-1.

In the all studies, the investigator set two fan controller settings (1) to achieve the desired air flow through the capturing hood (Q) and (2) to achieve the desired cross draft velocity through the wind tunnel (V_{cross}). Q was determined by 3 different prescribed frequencies ($\text{Freq}_{\text{Hoodfan}}$) which were inputted into the capturing hood fan controller. V_{cross} was controlled by setting the wind tunnel fan controller to 2 different rotation rates ($\text{Rotate}_{\text{WTfan}}$). Hence, $\text{Rotate}_{\text{WTfan}}$ and $\text{Freq}_{\text{Hoodfan}}$ are completely independent. Thus, ANOVA was performed with Q as the dependent variable and with $\text{Rotate}_{\text{WTfan}}$ and $\text{Freq}_{\text{Hoodfan}}$ as the independent variables using a fixed-effect model. The goal is to determine the degree that Q depends on its own controller frequency ($\text{Freq}_{\text{Hoodfan}}$) and the degree it depends on the V_{cross} controller value ($\text{Rotate}_{\text{WTfan}}$), which causes a higher static pressure in the wind tunnel.

Data from Preliminary Study Two and the Main Study was used for analysis in the study. Q should be strongly determined by $\text{Freq}_{\text{Hoodfan}}$. It is expected that Q is only modestly affected by $\text{Rotate}_{\text{WTfan}}$. If the latter is proved true, then in the main study Q and V_{cross} can be assumed to be largely independent.

Figure 7-1. Effect of Rotate_{WTfan} on Q

Table 7-1. Fixed-effect Analysis of Variance for dependent variable Q

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Constant	1	2.80E+07	2.80E+07	2.73E+05	≤0.0001
Freq _{HoodFan}	2	4.14E+06	2.07E+06	72789	≤0.0001
Rotate _{WTfan}	1	15710	15710	553	≤0.0001
Freq _{HoodFan} *Rotate _{WTfan}	2	3317.8	1659	58.383	≤0.0001
Error	42	1193	28		
Total	47	4.16E+06			

$$\text{ANOVA Model: } Y = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ij}$$

Where: α = Effect of Freq_{Hoodfan}
 β = Effect of Rotate_{WTfan}
 $\alpha\beta$ = Effect of interaction between Freq_{Hoodfan} and Rotate_{WTfan}

7.1 Results

As shown in Figure 7-1, Q was changed by a discernible but small amount by V_{cross} . Fixed-effect ANOVA results (see Table 7-1) show statistical significance ($p < 0.0001$) for Freq_{Hoodfan}, Rotate_{WTfan} and their interaction, the model is highly linear ($R^2 = 99.97$). A large proportion of the

variation is explained by $\text{Freq}_{\text{Hoodfan}}$ (99.5%) while $\text{Rotate}_{\text{WTfan}}$ and the interaction term only explain a small proportion of the variation (0.4%), given the model used. These results support the contention that values of Q are only modestly affected by $\text{Rotate}_{\text{WTfan}}$ and subsequently V_{cross} .

In conclusion, as expected the observed Q is only modestly, but significantly, dependent of $\text{Rotate}_{\text{WTfan}}$ and therefore V_{cross} . Thus, all analysis performed in this study uses a nominal value for Q (Q_{nom}) based on the average observed Q for each level of $\text{Freq}_{\text{Hoodfan}}$ to avoid interdependence of independent variables.

CHAPTER 8: MAIN STUDY RESULTS

The purpose of the main study was to determine the effects of the independent variables Q , V_{cross} , and Flange on C_{mouth} , C_{nose} , and C_{duct} .

Freon 134a concentrations were measured at the mouth (C_{mouth}) and nose (C_{nose}) of the manikin as well as inside the duct (C_{duct}) while the tracer gas mixture was released at the source in front of the capturing hood. The study was a complete randomized factorial design, including Q observed at 3 levels of $\text{Freq}_{\text{HoodFan}}$, V_{cross} based on two levels of wind tunnel fan rotation rate ($\text{Rotate}_{\text{WTfan}}$), and 2 levels of Flange (present and not present). All conditions were tested twice in a single random order.

As demonstrated in Preliminary Study Two, the airflow exhausted through the hood (Q) was affected by $\text{Freq}_{\text{HoodFan}}$ and, to a lesser degree, $\text{Rotate}_{\text{WTfan}}$. Hence, Q and V_{cross} are mutually dependent, however, the effect of V_{cross} on Q is small.

Table 8-1. Main study Freon concentrations for each level of independent variable.

$\text{Freq}_{\text{HoodFan}}$ Hz	Q cfm	V_{cross} fpm	Flange	C_{duct} ppm	C_{mouth} ppm	C_{nose} ppm	Calculated $\eta_{\text{e-G}}$	Calculated $\eta_{\text{e-100\%duct}}$
23	438.9	10	No	148.89	0.106	0.115	96.70%	94.44%
23	429.3	10	No	151.18	0.122	0.120	96.00%	95.89%
23	430.1	10	Yes	151.83	0.132	0.133	96.61%	96.31%
23	443.1	10	Yes	150.10	0.131	0.143	98.52%	95.21%
23	379.3	60	No	172.75	0.134	0.161	96.99%	109.57%
23	383.0	60	No	168.60	0.838	1.001	95.46%	106.94%
23	368.5	60	Yes	173.26	0.141	0.140	94.34%	109.90%
23	379.9	60	Yes	171.98	0.138	0.177	96.68%	109.09%
Average	406.5			161.07	0.218	0.249	96.41%	102.17%
40	796.9	10	No	84.44	0.120	0.280	99.70%	94.47%
40	800.4	10	No	85.68	0.105	0.114	101.75%	95.86%
40	803.9	10	Yes	86.73	0.101	0.121	103.55%	97.02%
40	804.9	10	Yes	92.37	0.104	0.112	110.85%	103.34%
40	767.8	60	No	96.44	0.125	0.144	110.34%	107.88%
40	771.5	60	No	83.01	0.115	0.102	94.59%	92.87%
40	768.0	60	Yes	90.26	0.118	0.117	102.90%	100.98%
40	769.0	60	Yes	91.88	0.104	0.134	105.02%	102.79%
Average	785.3			88.85	0.112	0.141	103.59%	99.40%

55	1108.4	10	No	61.78	0.123	0.117	101.49%	98.11%
55	1111.5	10	No	64.25	0.091	0.098	106.17%	102.03%
55	1117.7	10	Yes	67.58	0.122	0.123	112.66%	107.33%
55	1113.8	10	Yes	64.54	0.119	0.120	106.92%	102.50%
55	1086.1	60	No	67.80	0.125	0.129	109.64%	107.67%
55	1090.9	60	No	63.50	0.129	0.141	102.75%	100.84%
55	1095.5	60	Yes	65.34	0.119	0.125	106.39%	103.77%
55	1098.6	60	Yes	67.14	0.104	0.112	109.86%	106.63%
Average	1102.8			65.24	0.117	0.121	106.99%	103.61%
Overall Average					0.153	0.170	102.33%	101.73%

8.1 Protection Efficiency Results

Freon concentrations at the manikin's mouth (C_{mouth}) and nose (C_{nose}) were not corrected by subtracting the measured value of C_{ambient} from each test for a few reasons. One is that the Freon concentrations are very low, most values would be adjusted to zero or negative values (see Figure 8-1 and Figure 8-2). Second is that even without correction, it is clear that the concentrations are very low. Third is that measured values of C_{ambient} were all between 0.034 ppm and 0.132 ppm with a mean of 0.115 ppm, meaning that there was little build-up of Freon in the laboratory. Since Freon is not a common air contaminant, the Freon in the lab's ambient air is due to contaminants that have escaped from the capturing hood and have been mixed with the ambient air in the lab. One would reasonably expect C_{ambient} to be much lower than C_{mouth} and C_{nose} . The effect of Freon in the laboratory air may have been considered important if C_{ambient} was higher or more variable.

As shown in Table 8-1, Figure 8-1 and Figure 8-2, the Freon concentrations in the breathing zone of the manikin (C_{mouth} and C_{nose}) for each test were all below 1 ppm. All but one value for C_{mouth} and C_{nose} were above 0.2 ppm, a trivially low value only marginally higher than the room air concentration in the lab. Considering the very high Freon generation rate (1.79 lpm) and the extremely high concentration of Freon at the source (roughly 370,000 ppm), the capturing hood's protection was very nearly perfect (see Figure 8-3).

Figure 8-1. Measured Freon concentrations at the nose of the manikin and ambient locations for Q and Flange

Figure 8-2. Measured Freon concentrations at the mouth of the manikin and ambient locations for Q and Flange

As discussed in Chapter 1, there are several ways to calculate the protection efficiency (PE), none of which is ideal. Considering the concentration of Freon measured at C_{nose} and C_{mouth} the

PE is expected to be extremely high. The calculations for PE_G (Equation 1-5) and PE_{duct} (Equation 1-4) are presented here and are as expected, very high.

Table 8-2. Descriptive statistics for two measure of PE

	PE_G	PE_{duct}
Mean	100%	99.85%
Median	100%	99.86%
Std Dev	4.77E-07	0.000857
Range	2.4E-04%	4.26%
Minimum	99.997%	99.5%
Maximum	100%	99.93%

Figure 8-3. Protection efficiency based on C_{duct}

Figure 8-4. Protection efficiency based on G

8.2 Capture Efficiency Results

The capture efficiency is an important measure of hood performance because it evaluates the amount of contaminant that the hood will allow to escape into the work environment. It is not necessarily true that the extremely high protection efficiencies require extremely high capture efficiency. After all, the contaminant could simply be blown by V_{cross} downstream of the manikin and the hood, thus providing low C_{mouth} and C_{nose} but poor capture efficiency.

Note that the measured C_{duct} values were not adjusted for ambient concentrations because ambient concentrations were all less than 1% of measured duct concentrations.

Capture efficiency, η_e , was calculated in two different ways for the Main Study. One was based on the generation rate of the tracer gas (η_{e-G}) and Equation 1-2. The other was based on $C_{\text{duct-100\%}}$ ($\eta_{e-\text{duct100\%}}$) and Equation 1-3. In Preliminary Study Two, η_{e-G} was found to overestimate the true capture efficiency by 6.3%. Thus, for the main study, values of η_{e-G} were reduced by 6.3%.

In both cases the capture efficiency is partially based on observed values of C_{duct} . As shown in Figure 8-5, C_{duct} fell exponentially with increasing levels of airflow. Note that C_{duct} values for flanged and unflanged cases fell on the same curve, suggesting no improvement due to the flange. Hence, even though it was shown in Preliminary Study One that the flange increased V_x by 23% to 102%, it did not appear to improve η_e .

Figure 8-5. Measured Freon concentration in the duct when the tracer gas mixture was being released at the source for Q and Flange.

Figure 8-6. Calculated capture efficiency for Q and Flange based on $C_{\text{duct}100\%}$

Figure 8-7. Calculated capture efficiency for Q and Flange based on G.

CHAPTER 9: DISCUSSION OF THE MAIN STUDY RESULTS

The results suggest that the capturing hood was highly effective at controlling contaminant concentrations at the breathing zone of the manikin for all levels of the independent variables and in preventing escape into the room ambient air. However, there was a noticeable difference between the results for the two calculations of η_e .

As stated in previous chapters, when performing ANOVA analysis the average Q for each level of $\text{Freq}_{\text{Hoodfan}}$, expressed as the nominal value of Q (Q_{nom}), was used in place of the random variable Q which is modestly dependent on V_{cross} .

9.1 Effect of Independent Variables on $\eta_{e\text{-duct100\%}}$

The capture efficiency was computed in two different ways. Using Equation 1-3, $\eta_{e\text{-duct100\%}}$ was computed as the ratio of C_{duct} to the corresponding concentrations average $C_{\text{duct-100\%}}$ concentration shown in Table 6-2. The latter were measured in Preliminary Study Two when 100% capture was assured ($C_{\text{duct-100\%}}$).

As shown in Table 8-1, $\eta_{e\text{-duct100\%}}$ values were greater than 92% for all conditions and 63% of the values exceeded 100%. The average value was 101.7%, despite being effectively normalized for the average $C_{\text{duct-100\%}}$ value found in preliminary study two (see Figure 6-1).

Table 9-1. Fixed-effect Analysis of Variance for dependent variable $\eta_{e-duct100\%}$

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	248361.0	248361.0	18488.0	≤ 0.0001
Q_{nom}	2	72.7	36.3	2.7	0.0992
V_{cross}	1	243.3	243.3	18.1	0.0007
Flange	1	33.3	33.3	2.5	0.1363
$Q_{nom} * V_{cross}$	2	150.4	75.2	5.6	0.0153
$Q_{nom} * \text{Flange}$	2	6.4	3.2	0.2	0.7911
Error	15	201.5	13.4		
Total	23	707.6			

$$\text{ANOVA Model: } Y = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \varepsilon_{ijkl}$$

Where:

- α = Effect of Q_{nom}
- β = Effect of Rotate_{WTfan} or V_{cross}
- γ = Effect of Flange
- $\alpha\beta$ = Effect of Interaction between Q_{nom} and Rotate_{WTfan}
- $\alpha\gamma$ = Effect of Interaction between Q_{nom} and Flange

Using ANOVA with a fix-effect model and $\eta_{e-duct100\%}$ as the dependent variable, the effect of V_{cross} was the only variable found to be significant ($p=0.0007$) based on the model used. Surprisingly the effect of V_{cross} on $\eta_{e-duct100\%}$ was in the opposite direction than expected, with $V_{cross} = 10$ fpm causing a lower $\eta_{e-duct100\%}$ and $V_{cross} = 60$ fpm causing a higher $\eta_{e-duct100\%}$ (see Table 8-1). It is reasonable to speculate that the cross draft carried the contaminant towards the hood face causing an increase in capture efficiency. If this explanation is correct, it is likely that if V_{cross} was not oriented towards the hood face that the capturing efficiency would be much lower.

9.2 Effect of Independent Variables on η_{e-G}

Using Equation 1-2, η_{e-G} was calculated using the observed air flow through the hood (Q), the generation rate (G), and concentration of Freon measured in the duct (C_{duct}). The results were then adjusted by subtracting 6.3% from each value. The latter was based on the Preliminary Study One results, which showed an average efficiency of 106.3% instead of the expected value

of 100%. As show in Table 8-1, the resulting minimum efficiency was greater than 94%. The average was 107% and the maximum was 112%. Even with a downward adjustment the efficiencies were still impossibly high.

Table 9-2. Fixed-effect Analysis of Variance for η_{e-G}

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	251306.0	251306.0	15675.0	≤0.0001
Q_{nom}	2	466.1	233.0	14.5	0.0003
V_{cross}	1	1.5	1.5	0.1	0.766
Flange	1	44.6	44.6	2.8	0.116
$Q_{nom} * V_{cross}$	2	2.3	1.1	0.1	0.9321
$Q_{nom} * \text{Flange}$	2	18.4	9.2	0.6	0.5748
Error	15	240.5	16.0		
Total	23	773.329			

$$\text{ANOVA Model: } Y = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \varepsilon_{ijk}$$

Where:

- α = Effect of Q_{nom}
- β = Effect of Rotate_{WTfan} or V_{cross}
- γ = Effect of Flange
- $\alpha\beta$ = Effect of Interaction between Q_{nom} and Rotate_{WTfan}
- $\alpha\gamma$ = Effect of Interaction between Q_{nom} and Flange

When the capture efficiency is calculated using the generation rate and analyzed using a fix-effect ANOVA model only the effect of Q_{nom} is found to be significant at $p < 0.0003$. This result was expected because of the strong effect of Q_{nom} observed on V_x .

9.3 Comparison of Two Measures of Capture Efficiency: η_{e-g} and $\eta_{e-duct100\%}$

The two measures of capture efficiency used should have a linear relationship with a slope of unity and an intercept of zero because they are essentially the same measures.

Comparison of Capture Efficiency Measures

Figure 9-2. Comparison of two measures of capture efficiency

Comparison of Capture Efficiency Measures

Figure 9-3. Comparison of two measure of capture efficiency with four values removed

With the four measures from $\text{Freq}_{\text{HoodFan}}=23$ Hz removed, the correlation between the two capture efficiencies improves dramatically from an R^2 of 0.118 to 0.869. This suggests that η_{e-G} may be a better measure of capture efficiency than $\eta_{e-\text{duct}100\%}$ because it is less subject to the influence of the cross draft.

9.4 Effect of Independent Variables on PE

The measured concentrations for tracer gas in the breathing zone of the manikin, C_{nose} and C_{mouth} , were extremely low for all conditions tested (<1ppm) with nearly all below 0.15ppm. The resulting protection efficiencies were extremely high (>99.5%). Since these concentrations were trivially low, the effect of independent variables on the protection efficiency are of little interest for these data. Unsurprisingly given the lack of diversity in the values of C_{nose} and C_{mouth} , ANOVA was performed using a fixed-effect model, both measures showed no significant effects for the independent variables (see Table 9-3 and Table 9-4).

Table 9-3. Fixed-effect analysis of variance for the dependent variable C_{mouth}

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	0.69326	0.69326	22.089	0.0003
Q_{nom}	2	0.076078	0.038039	1.212	0.3251
V_{cross}	1	0.032782	0.032782	1.0445	0.323
Flange	1	0.038801	0.038801	1.2363	0.2837
$Q_{\text{nom}}*V_{\text{cross}}$	2	0.086759	0.043379	1.3822	0.2812
$Q_{\text{nom}}*\text{Flange}$	2	0.045046	0.022523	0.71765	0.5039
Error	15	0.470768	0.031385		
Total	23	0.750233			

Table 9-4 Fixed-effect analysis of variance for the dependent variable C_{nose}

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	0.529848	0.529848	25.19	0.0002
Q_{nom}	2	0.057508	0.028754	1.367	0.2849
V_{cross}	1	0.027608	0.027608	1.3125	0.2699
Flange	1	0.020417	0.020417	0.97064	0.3401
$Q_{\text{nom}}*V_{\text{cross}}$	2	0.04478	0.02239	1.0645	0.3696
$Q_{\text{nom}}*\text{Flange}$	2	0.033886	0.016943	0.80551	0.4653
Error	15	0.315512	0.021034		
Total	1	0.529848	0.529848	25.19	0.0002

$$\text{ANOVA Model: } Y = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \varepsilon_{ijkl}$$

Where:

- α = Effect of Q_{nom}
- β = Effect of Rotate_{WTfan} or V_{cross}
- γ = Effect of Flange
- $\alpha\beta$ = Effect of Interaction between Q_{nom} and Rotate_{WTfan}
- $\alpha\gamma$ = Effect of Interaction between Q_{nom} and Flange

With V_{cross} oriented towards the back of the manikin was expected to cause a wake zone effect in front of the manikin which would convey the contaminant back into the breathing zone of the manikin. This effect was not seen in these results. It is plausible the V_{cross} simply pushed the contaminant further downstream, way from the manikin's breathing zone, causing the extremely high protection efficiencies. However, the extremely high capture efficiencies argue that the PE values were low simply because the hood was extremely effective at capturing the contaminant.

9.5 Smoke Visualization

Smoke was released to visualize the apparent effectiveness of the hood. A Model 1741 Fog Machine manufactured by Multi Media Electronics, Inc. was used to generate smoke. Smoke was conveyed to the tracer gas source in front of the hood using the tubing employed for the tracer gas delivery system. A helium stage light was utilized to illuminate the smoke released at the source. Each test from the main study was done once.

Table 9-5. Result of Smoke Visualization

$Freq_{Hood fan}$ Hz	V_{cross} fpm	Flange	Flow Disturbed	Smoke behavior
23	10	No	Yes	Followed table surface to hood, low lying. No movement back towards manikin. Slow moving. Easily disturbed.
23	10	Yes	No	Moved more directly towards hood, some followed table surface most rose and entered middle of hood.
23	60	No	Yes	Moved towards manikin's body, rose to about mid chest before entering the hood
23	60	Yes	Yes	Slight movement towards manikin. Part followed table surface most rose and entered middle of hood
40	10	No	No	Entrainment of at the trailing edge of source. Entered lower half of hood. Fast moving.
40	10	Yes	No	Entrainment of at the trailing edge of source. Fast moving.
40	60	No	Yes	Little turbulence at source, no movement towards manikin. Fast moving.
40	60	Yes	No	Entrainment of at the trailing edge of source. Fast moving.
55	10	No	No	Pulled directly into the hood. Very fast moving.
55	10	Yes	No	Pulled directly into the hood. Very fast moving.
55	60	No	No	Pulled directly into the hood. Very fast moving.
55	60	Yes	No	Pulled directly into the hood. Very fast moving.

For tests where $V_{cross}=10$ fpm and $Freq_{Hood fan}=23, 40$ and 55 , the smoke released from the source was captured with little to no observed disturbance to the smoke and with no visible escape from the hood. The difference in behavior of the smoke released from the source can be observed at different levels of $Freq_{Hood fan}$ and with the addition of a flange (see Figure 9-6 and Figure 9-7). However when $Freq_{Hood fan}$ was 23 Hz, the manikin's wake zone appeared to have an influence on the smoke being released at the source (see Figure 9-4). At a $V_{cross}=60$ fpm the smoke would periodically travel towards the mid-section of the manikin and rise to the mid chest of manikin before being pulled into the hood. Smoke was not observed to rise above the neck of the manikin.

Figure 9-4. Smoke visualization tests at $\text{Freq}_{\text{HoodFan}} = 23$ and $\text{Rotate}_{\text{WTfan}} = 930$ with no flange.

Figure 9-5. Smoke Visualization at $\text{Freq}_{\text{HoodFan}} = 23$ $\text{Rotate}_{\text{WTfan}} = 930$ with and without a flange.

Figure 9-6. Smoke visualization at $\text{Freq}_{\text{HoodFan}} = 40$ $\text{Rotate}_{\text{WTfan}} = 930$ with and without a flange.

Figure 9-7. Smoke visualization at $\text{Freq}_{\text{HoodFan}} = 55$ and $\text{Rotate}_{\text{WTfan}} = 930$ with and without a flange.

CHAPTER 10: CONCLUSIONS

The small capturing hood tested controlled C_{nose} and C_{mouth} to very nearly zero ppm, which was much better than expected. The protection efficiency was nearly 100% in every case, providing too little diversity for statistical evaluations of the effects of independent variables. Observation of smoke released at the tracer gas source showed no escape from the hood, suggesting that any escape was too minor to see under the conditions.

The capture efficiency ranged from 92% to 110% when calculated with $C_{\text{duct}100\%}$ and 94% to 112% when calculated with the generation rate and observed Q . Because of the difficulty in measuring at these concentrations with acceptable precision and accuracy, little confidence should be placed in the capture efficiency results.

The results of this study seem to support Industrial Ventilation's suggestion that capture hoods can be effective if kept close enough to the source to induce a substantial velocity. The reason they may sometimes be highly ineffective is that workers often move the hood or the contaminant source to a distance where the capture velocity approaches the values of convection currents and cross drafts. Since the capture velocity falls with the distance squared from the hood face, even small movements can lead to inadequate capture velocities.

10.1 Caveats

It's important to note that study tested only one hood in a highly artificial environment of a wind tunnel for one direction of cross draft with a fixed distance between the source and the hood face. Changing any of the studied parameters may yield dramatically different results.

Likewise, the manikin was placed in a non-moving, fixed posture and had no body or hand movements. If the manikin or its hands moved, the results may have been very different.

10.2 Recommendations

Further study with different cross-draft orientations, source distance, and manikin movements should be done before attempting to apply these results in practical applications. For measures

of capture efficiency, more accurate and precise measurements at the levels found in the duct are needed.

CHAPTER 11: REFERENCES

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Appendix I. FTIR Calibration

The FTIR was calibrated twice, once before and once after testing, by adding ultra-high purity Freon in varying amounts to 9 liters of air laboratory air in a 10 liter Tedlar® bag using gas tight syringes. Varying amounts of the Freon mixture was drawn from the 10 liter bag and injected to in to 5 liter Tedlar bag using a 3 liter syringe. The bag was diluted with laboratory air, if needed, to achieve the desired concentration of Freon. The bags were then analyzed by the FTIR. The residual values for the calibration were also recorded to determine if some measured concentrations resulted in higher residual values. The investigator found that for measured concentrations between approximately 50 to 100 ppm the FTIR returned an error associated with the sample (residual >0.02).

Figure 11-1. Calibration curve for the FTIR, combined pre and post calibrations.

Figure 11-2. Residual values associated with the measured Freon concentrations during calibration.

Dilutions techniques were developed and implemented to avoid range of concentrations which returned high residuals (errors) during the study. Even though the FTIR calibration curve shows that the measured concentrations with errors fit on a line with the measured concentrations which did not receive errors, which suggests that the values with errors may not be in fact erroneous, the FTIR manual clearly states that samples with error statements should never be used.

Appendix II. CTA Calibration and Directional Sensitivity

The CTA was calibrated using the TSI, Inc. Model 1125 calibrator, hooked to laboratory air supply, with the probe in the upper chamber of the unit 2 chamber, and the PVM-100 for velocity pressure measurement from the camber. Temperature and pressure in the laboratory were recorded and used for calculations of velocity from velocity pressure during calibration. The pressure inside the chamber was increased from 0 to 0.8 inch of water to achieve a velocity range of approximately 0 to 200 fpm.

$$V = 4005 \sqrt{\frac{VP}{df}}$$

Where:

- VP = Velocity pressure
- df = Corrective factor for temperature and pressure
- V = Velocity in the chamber

Table 11-1. CTA Calibration

Seq No	<u>meas VP</u>	<u>meas Voltage</u>	<u>calibrator Position</u>	Chamber Vel from <u>VP</u>
1	0.000	1.42727	1	0.00
2	0.049	1.50118	1	47.97
3	0.1	1.52881	1	68.52
4	0.15	1.54703	1	83.92
5	0.199	1.56055	1	96.67
6	0.302	1.58206	1	119.08
7	0.399	1.59728	1	136.88
8	0.500	1.61026	1	153.22
9	0.600	1.62152	1	167.85
10	0.700	1.63099	1	181.30
11	0.800	1.63975	2	193.82

Figure 11-3. CTA calibration curve.

The equation present above in Figure 11-3 was entered in the National Instruments Signal Express program to correct correlate measured voltage to velocity in fpm.

Figure 11-4. Directional sensitivity of the CTA when rotated about its axis.

The directional sensitivity of the CTA was measured by rotating the CTA along the axis of the probe at 45 degree intervals. The reduction in calculated velocity from the CTA for each interval

around the axis of the CTA is shown in Figure 11-4. The CTA probe was found to have a minimal response of approximately 18% when the probe was oriented 90 degrees to the direction of the flow and a response of approximately 45% when the probe oriented at a 45 degree angle to the direction of flow. The percent response was calculated as the measured velocity at an abnormal position (45, 90, 225, 270, and 315 degrees) divided by the measured velocity when the probe was positioned "normally" with the wire perpendicular to the flow (0 and 180 degrees).0