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Robust heating in crisis - Evaluation of the FirePipe emergency stove for indoor environments in cold climates

Master's thesis in Structural Engineering and Building Technology

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Gothenburg, Sweden 2026
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MASTER'S THESIS 2026

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The new improved stove solution is evaluated for its performance and function in real winter conditions to analyse its impact on indoor environment.

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Cover: Image of improved stove setup in the building .

Typeset in L^AT_EX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2026

Abstract

The FirePipe emergency stove is a flat packed, indoor stove with a window mounted flue, designed to provide space heating, cooking capability, and water boiling during emergencies. While previous laboratory testing and short term evaluations have confirmed its basic functionality and fire safety, there is limited knowledge of how the stove performs in real environments under dynamic indoor and outdoor conditions.

This study investigates how the FirePipe stove interacts with indoor environmental conditions during winter use. The research evaluates whether the stove can maintain acceptable indoor temperatures and safe air quality. Indoor climate and air quality parameters, including temperature distribution and concentrations of CO, CO₂, PM_{2.5}, PM₁₀, and ultrafine particles (UFP), are measured and analyzed across different operational phases.

In addition, the influence of external weather conditions, including wind speed, wind direction, and outdoor temperature, on stove performance and indoor air quality is examined. The study also assesses user friendliness, installation procedures, and the accompanying manual to identify potential improvements. Based on these findings, the work provides recommendations for safe use and identifies scenarios in which the stove should not be used.

Keywords: Emergency heating, FirePipe stove, indoor air quality, air quality monitoring, pollutant concentration, emission sources, indoor air pollution, particulate matter (PM_{2.5}, PM₁₀), ultrafine particles (UFP), carbon monoxide exposure (CO), carbon dioxide concentration (CO₂).

Acknowledgements

This master's thesis was conducted at the Department of Architecture and Civil Engineering, Division of Building Services Engineering, at Chalmers University of Technology.

I would like to express my sincere gratitude to Professor Lars Ekberg, who served as both examiner and supervisor, for his guidance, constructive feedback, and continuous support throughout the thesis work.

I am especially thankful to Håkan Larsson, who supervised the laboratory work and provided invaluable assistance with equipment handling and experimental procedures. His practical expertise and support were essential during both the laboratory and field measurements.

I would also like to acknowledge Gustav Widström and Stefan Rahmqvist at Cut and Fold Sweden AB, whose collaboration made this study possible. Their support ensured that the device and experimental setup met the required standards.

Furthermore, I am grateful to Patrik Selhag at Poseidon AB for his support during the field testing. He facilitated access to suitable testing locations and provided continuous assistance throughout the experimental phase.

Finally, I would like to extend my heartfelt thanks to my family and friends for their encouragement and understanding throughout my academic journey. Their support has been invaluable in completing this thesis.

Anusha Sridharan, Gothenburg, 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ACH	Air Change Hour
CPC	Condensation Particle Counter
EC	Electronically Commutated
FETA	Federation of Environmental Trade Associations
PM	Particulate Matter
RH	Relative Humidity
SMHI	Swedish Meteorological and Hydrological Institute
TOC	Total Organic Volatile Compound
UFP	Ultrafine Particles
VOC	Volatile Organic Compound

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables used throughout this thesis.

pt/cc	Particles per Cubic Centimeter
mg/m ³	Milligrams per Cubic Meter
ppm	Parts per Million
°C	Celsius
m ³ /hr	Cubic Meter per Hour
m ³	Cubic Meter
CO ₂	Carbon Dioxide
CO	Carbon Monoxide
Δp	Differential pressure
T_g	Globe temperature
T_{room}	Room temperature
Q	Ventilation Flow Rate
V	Room Volume
C ₀	Initial Indoor CO ₂ Concentration
C ₁	Final Indoor CO ₂ Concentration
C _R	Outdoor/Background CO ₂ Concentration

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1

Introduction

1.1 Background

Residential buildings in Sweden are highly dependent on centralized energy systems, particularly district heating and hot water, which represent the most basic requirements for comfortable and habitable living conditions. These systems are designed to operate through interconnected energy grids, substations, and centralized power plants. In the event of a major disruption, such as a natural disaster or a sociopolitical crisis, including war, the functioning of these systems may be severely compromised. Damage to substations, grid nodes, or transmission infrastructure, whether caused by natural forces or deliberate attacks, could result in a largescale failure of district heating and hot water supply throughout the country. A further structural vulnerability of the Swedish energy system lies in the geographical mismatch between energy production and consumption. A significant proportion of power generation facilities are located in the northern regions of Sweden, whereas energy demand is considerably higher in the southern regions due to greater population density. This imbalance necessitates long distance high voltage transmission lines connecting north and south, which increases system vulnerability during crisis scenarios. Any damage to these transmission corridors could lead to widespread power shortages in the southern regions.

In addition, Sweden relies heavily on critical imports from neighboring countries, including semiconductors and other essential electrical components. In a crisis situation, such imports may be difficult or impossible to procure, thereby delaying repairs and resulting in prolonged grid outages. Sweden's energy mix also relies strongly on renewable energy sources, particularly wind power. However, wind energy production varies significantly throughout the year and cannot be guaranteed during emergency situations. Under such circumstances, importing electricity from neighboring countries may also not be feasible. To address vulnerabilities in the energy system, the Swedish government has increased its focus on energy resilience and crisis preparedness. This includes investments in emergency capacity measures such as gas turbines, as well as discussions on improving local and regional robustness within the electricity system. Although Sweden continues to rely primarily on the centralized national grid, there is growing interest in strengthening the ability of critical energy infrastructure and local systems to maintain functionality during

disruptions or emergency situations. This shift highlights the growing importance of decentralized and household level energy solutions that can provide basic services in the event of prolonged system failure.

1.2 Motivation

In response to these challenges, FirePipe, in collaboration with RISE, has developed an indoor emergency stove made of carbon steel. The stove is designed as a flat packed unit with minimal tool assembly and features a routed flue system that can be installed through a window. This design allows for rapid deployment, ease of transport, and installation without permanent modifications to the building.

The stove has been demonstrated to be capable of providing space heating, cooking functionality, and the possibility of boiling and purifying water. The product is currently included in municipal emergency stockpiles and has also been deployed in Ukraine, where it has proven effective under real crisis conditions.

A recently improved installation solution has undergone evaluation at RISE in accordance with selected sections of EN16510-1:2022, focusing on fire safety requirements. Despite these developments, previous experimental investigations of the FirePipe stove have largely been limited to short term laboratory based testing under controlled conditions. These studies have not considered long term performance or operation across different seasons, particularly during winter conditions. This study addresses that limitation.

1.3 Research Gap

Most existing research on indoor emergency heating systems has focused on laboratory-based testing, emphasizing fire safety, thermal efficiency, and pollutant emissions under controlled conditions. While such testing is essential, it does not adequately represent real world residential environments. Laboratory studies typically do not capture the complexity and variability of actual dwellings, where numerous dynamic factors influence indoor conditions. In addition, the robustness of emergency heating systems under varying outdoor weather conditions remains insufficiently explored.

Real world experiments in occupied buildings are often avoided due to safety concerns, the potential risk posed to occupants, privacy related issues, and the labor-intensive nature of installing extensive monitoring equipment. As a result, many existing results are based on laboratory data and fail to represent the dynamic nature of real indoor environments during emergencies.

There is therefore a lack of quantitative understanding regarding the interaction between indoor emergency stoves, indoor climate, and indoor air quality in actual field settings. Key parameters such as carbon monoxide (CO), carbon dioxide (CO₂), particulate matter (PM_{2.5}, PM₁₀), ultrafine particles (UFP), other organic compounds,

flue gas behavior, and occupant exposure levels have not been comprehensively evaluated in real residential scenarios.

1.4 Aim and Objectives

1.4.1 Aim

The primary aim of this master's thesis is to develop a quantitative understanding of the interaction between an indoor emergency stove and dynamic environmental conditions under realistic field conditions. The study is conducted in a firefighter training facility designed to simulate real world emergency scenarios.

1.4.2 Objectives

The specific objectives of the study are as follows:

- To evaluate the user friendliness of the FirePipe stove, including installation and operation based on the provided instruction manual, and to propose improvements where necessary.
- To measure and analyze indoor environmental conditions during stove operation, including:
 - Indoor air temperature at multiple locations,
 - Concentrations of pollutants such as CO, CO₂, organic compounds, ultrafine particles (UFP), particulate matter (PM_{2.5}, PM₁₀), and flue gases.
- To assess whether the FirePipe stove can maintain indoor temperatures within acceptable limits under typical Swedish winter conditions.
- To investigate pressure differences between the indoor space and the outdoor environment under varying conditions. This includes analyzing differential pressure and airflow rates to simulate extreme outdoor scenarios and determine safe operating conditions for the stove. The study further aims to identify the pressure and airflow conditions under which optimal stove performance, indoor comfort, and air quality are achieved in the absence of mechanical ventilation systems.

1.5 Limitations

The study is based on measurements conducted within a single fire training room rather than an entire residential building. Therefore, the findings cannot be generalized to all residential settings but may serve as a reference for similar environments under comparable conditions. Additionally, the study is specific to the climatic conditions of Gothenburg, Sweden, which limits its applicability to other regions.

The experimental campaign is conducted over a one week period in March and does not cover a full annual cycle. Consequently, variations across different seasons are not fully captured. Furthermore, in real residential environments, factors such as stove operation patterns, window opening behavior, and occupant activities cannot be entirely controlled. These variables may influence measurement accuracy, partic-

ularly during refueling events, when data collection may be temporarily interrupted. Such occurrences are documented during the study.

Although the test environment is designed to represent realistic indoor conditions, it does not replicate all aspects of residential dwellings, including furniture arrangements, occupant behavior, and variations in insulation. Therefore, the results should be interpreted as indicative of general indoor conditions under controlled field scenarios rather than being specific to any particular building type.

2

Theory

2.1 Introduction

Residential wood combustion is widely used for domestic heating and cooking in many regions of the world. In addition to conventional residential heating applications, temporary wood burning stoves may also be used during emergency situations such as war, natural disasters, or power outages where electricity and conventional mechanical ventilation systems may not be available. Under such conditions, stove performance becomes strongly dependent on natural airflow conditions, chimney draft, combustion stability, and pressure differences between indoor and outdoor environments. These factors directly influence combustion efficiency, pollutant emissions, indoor air quality, and operational safety [1].

Although wood is considered a renewable fuel source, wood combustion can generate substantial quantities of harmful air pollutants, especially under incomplete combustion conditions. According to the Swedish Environmental Protection Agency, emissions from residential wood burning include particulate matter, soot, hydrocarbons, carbon monoxide, and other combustion related compounds negatively affect both human health and the environment [1]. The quantity of emissions produced depends on several factors including combustion temperature, fuel quality, stove design, airflow conditions, chimney performance, and firing practices.

Indoor exposure to pollutants generated from wood burning appliances has become an increasingly important research topic because emissions may accumulate inside occupied spaces during ignition, fuel loading, leakage, or unstable draft conditions. Several studies have shown that wood stove operation may significantly increase indoor concentrations of particulate matter, ultrafine particles, black carbon, and carbon monoxide [2], [3]. Pollutant transport and indoor accumulation are strongly influenced by ventilation conditions, airflow behavior, pressure balance, and leakage within the stove and chimney system.

The present study investigates the operation of a temporary wood stove under controlled indoor pressure conditions. Particular emphasis is placed on combustion behavior, airflow patterns, chimney draft, leakage, particle emissions, and carbon monoxide formation. The following sections review previous studies and theoretical concepts relevant to wood combustion, pollutant formation, indoor air quality, airflow behavior, pressure conditions, and health effects associated with residential

wood burning.

2.2 Wood Combustion and Pollutant Formation

Wood combustion is a complex process consisting of drying, pyrolysis, flaming combustion, and char combustion. Efficient combustion requires sufficient oxygen supply, adequate combustion temperature, and effective mixing between combustible gases and incoming air. When these conditions are achieved, combustion becomes more complete and pollutant emissions are reduced. However, poor combustion conditions may result in incomplete combustion, leading to elevated emissions of smoke, soot, particulate matter, hydrocarbons, and carbon monoxide [4].

The Swedish Environmental Protection Agency identifies insufficient oxygen supply, low combustion temperatures, damp fuel, and poor firing practices as major contributors to increased emissions from residential wood burning appliances [1]. Incomplete combustion prevents full oxidation of the gases released during wood pyrolysis, resulting in increased smoke formation and elevated pollutant concentrations.

The ignition phase is considered particularly critical because combustion conditions are initially unstable. During ignition, the combustion chamber and chimney remain relatively cold, resulting in weak chimney draft and unstable airflow through the stove. As combustion intensifies and temperatures increase, buoyancy forces strengthen the upward movement of hot gases within the chimney, thereby improving draft conditions and combustion stability [5].

Several studies have shown that the ignition phase often produces the highest short-term pollutant peaks due to unstable combustion and fluctuating airflow conditions. Sundell et al. [3] observed that particle concentrations increased significantly during ignition and early combustion stages due to incomplete combustion and unstable chimney draft behavior.

Fuel quality also strongly influences combustion performance. The Swedish Environmental Protection Agency recommends the use of dry wood with moisture contents of approximately 15–20% [4]. Wet fuel requires additional energy for water evaporation, thereby reducing combustion temperature and increasing emissions of smoke and pollutants.

The Stove Industry Association further emphasizes that adequate combustion air supply is essential for maintaining efficient stove operation and reducing indoor pollutant emissions. Restricted airflow during ignition and combustion may result in unstable flames, smoke leakage, and elevated indoor particle concentrations [6].

2.3 Particulate Emissions from Wood Burning

2.3.1 PM_{2.5} and PM₁₀

Particulate matter generated during wood combustion is commonly classified according to aerodynamic diameter, particularly PM_{2.5} and PM₁₀. PM_{2.5} refers to particles smaller than 2.5 μm , while PM₁₀ refers to particles smaller than 10 μm [7]. Combustion generated emissions are generally dominated by fine particles, particularly during incomplete combustion conditions.

According to the Swedish Environmental Protection Agency, fine particles produced during wood combustion are among the most harmful air pollutants because they are sufficiently small to penetrate deeply into the respiratory tract and lungs [7]. Exposure to PM_{2.5} has been associated with respiratory disease, cardiovascular disease, lung cancer, and premature mortality.

Molnár et al. [2] investigated indoor air pollution associated with residential wood combustion in Sweden and observed elevated indoor particle concentrations during stove operation. The study demonstrated that indoor particle exposure is strongly influenced by combustion behavior, ventilation conditions, and airflow patterns within the room. Indoor concentrations increased significantly during active combustion periods and emission events.

The SMHI population exposure assessment further highlights that PM_{2.5} exposure remains a major public health concern in Sweden and identifies residential wood combustion as an important contributor to wintertime particulate emissions [8]. Although outdoor exposure is commonly discussed, indoor exposure may also become substantial during ignition, fuel loading, leakage, or unstable combustion conditions.

The FETA indoor air quality fact sheet additionally states that indoor particulate concentrations may increase considerably during wood stove operation, especially when ventilation conditions are poor or when smoke leakage occurs from stove systems [9]. These findings are directly relevant to the present study, where PM₁, PM_{2.5}, and PM₁₀ concentrations were continuously monitored during different combustion and ventilation conditions.

2.3.2 Ultrafine Particles

Ultrafine particles are generally defined as particles smaller than 100 nm in diameter. Unlike PM_{2.5} and PM₁₀, ultrafine particle exposure is commonly evaluated using particle number concentration rather than particle mass concentration. Wood combustion is considered an important indoor source of ultrafine particle emissions.

The Clean Heat study investigating indoor ultrafine particle pollution from residential wood stoves demonstrated that stove operation can result in substantial increases in indoor ultrafine particle concentrations [10]. Elevated concentrations

were particularly associated with ignition, fuel loading, smoke leakage, and unstable combustion conditions. Leakage through stove doors, smoke pipe joints, and reverse airflow through chimneys were identified as important contributors to indoor ultrafine particle exposure.

Measurements conducted using P-Trak instruments also showed strong spatial variation in ultrafine particle concentrations around stove systems and chimney interfaces. High concentrations were observed near smoke pipe joints, stove seams, and chimney interfaces, indicating that combustion products may enter the indoor environment through unintended airflow paths [10].

Molnár et al. [2] similarly reported that residential wood combustion contributes significantly to indoor ultrafine particle exposure. Their study showed that particle concentrations increased rapidly during active combustion phases and that indoor concentrations were strongly influenced by stove operation and ventilation conditions. Combustion generated particles were also observed to remain suspended indoors depending on room airflow patterns and air exchange rates.

Recent research published in Scientific Reports observed elevated ultrafine particle concentrations during biomass stove operation and identified ventilation conditions, combustion stability, and room pressure as important factors influencing indoor pollutant accumulation [3]. The study highlighted that ignition and fuel loading phases are associated with particularly high short term particle peaks.

Research published in Atmospheric Environment further identified residential biomass combustion as an important source of ultrafine particle emissions and emphasized that combustion-generated aerosols may remain suspended indoors depending on airflow conditions and ventilation behavior [11]. The study also discussed how airflow conditions influence particle transport and indoor exposure patterns.

These findings are directly relevant to the present study because localized ultrafine particle measurements were conducted using both stationary and mobile P-Trak instruments around the stove, chimney joints, and leakage interfaces to investigate pollutant transport and airflow behavior.

2.4 Carbon Monoxide and Indoor Combustion Safety

Carbon monoxide is a colorless and odorless gas produced during incomplete combustion. In wood burning systems, elevated carbon monoxide formation is associated with insufficient oxygen supply, unstable combustion conditions, poor draft, and inadequate ventilation [12].

Indoor accumulation of carbon monoxide may occur when combustion gases cannot be effectively removed through the chimney system. Conditions such as backdraft, reverse airflow, chimney blockage, or inadequate air supply may therefore contribute to elevated indoor CO concentrations [12].

The Swedish Environmental Protection Agency emphasizes that proper airflow and stable combustion conditions are essential for reducing carbon monoxide emissions [4]. Incomplete combustion resulting from insufficient airflow increases the production of carbon monoxide and other harmful combustion-related pollutants.

Studies investigating indoor biomass combustion have shown that carbon monoxide concentrations may increase rapidly during ignition and fuel loading due to unstable airflow conditions and temporary combustion inefficiencies [3]. These transient combustion phases are therefore considered particularly important from an indoor air quality and safety perspective.

The FETA indoor air quality guidance also highlights that poor ventilation and leakage from combustion appliances may increase indoor exposure to combustion gases, particularly in poorly ventilated indoor environments [9].

These findings are directly relevant to the present study because carbon monoxide concentrations were continuously monitored during ignition, combustion, ventilation interventions, and fuel loading conditions.

2.5 Airflow, Pressure Conditions, and Chimney Draft

Airflow behavior within wood burning systems is strongly influenced by pressure differences and chimney draft. Chimney draft is generated primarily by buoyancy forces resulting from temperature differences between hot combustion gases inside the chimney and cooler outdoor air. As hot gases rise upward through the chimney, air is drawn into the combustion chamber to sustain combustion [5].

Stable chimney draft is essential for maintaining efficient combustion and preventing smoke leakage into occupied spaces. However, during ignition or under unfavorable pressure conditions, chimney draft may become unstable, increasing the likelihood of smoke spillage and backdraft [4].

Pressure conditions inside the room also strongly influence stove behavior. Under negative pressure conditions, air may enter through unintended openings such as chimney joints, stove seams, or installation gaps. The Clean Heat study identified reverse airflow and leakage through chimney systems as important contributors to indoor ultrafine particle exposure [10].

The Stove Industry Association further emphasizes that sufficient combustion air supply is necessary for maintaining safe stove operation and minimizing indoor pollutant emissions [6]. Insufficient air supply may disturb combustion stability and increase the risk of smoke leakage and incomplete combustion.

Recent studies investigating biomass stove emissions have shown that airflow be-

havior and ventilation strongly influence pollutant transport and indoor particle accumulation [3]. Changes in room pressure and ventilation conditions may therefore significantly affect indoor pollutant concentrations and leakage behavior.

The present study specifically investigates the relationship between pressure conditions, airflow behavior, chimney draft, and pollutant transport using controlled ventilation conditions established through an extract fan and damper system.

2.6 Leakage and Stove Installation

Installation quality and chimney configuration play important roles in determining stove performance and indoor air quality. Leakage may occur through stove seams, smoke pipe joints, chimney interfaces, and stove doors. Such leakage becomes increasingly significant under unstable draft conditions and negative pressure environments [10].

The Clean Heat study observed elevated ultrafine particle concentrations near smoke pipe joints and stove seams, indicating that leakage through these locations contributes significantly to indoor pollutant exposure [10]. Similar findings have also been reported in studies investigating indoor biomass combustion emissions [2], [3].

Chimney geometry may additionally influence airflow stability. Vertical chimney sections generally support buoyancy driven airflow more effectively, whereas horizontal sections may increase airflow resistance and disturb draft behavior. Studies investigating biomass combustion systems have identified chimney configuration as an important factor influencing combustion stability and indoor leakage behavior [11].

These findings are directly relevant to the present study because elevated ultrafine particle concentrations were measured near horizontal chimney sections and chimney joints during stove operation.

2.7 Health Effects of Residential Wood Burning

Residential wood combustion contributes to both indoor and outdoor exposure to harmful air pollutants. According to the Swedish Environmental Protection Agency, exposure to wood smoke is associated with respiratory and cardiovascular health effects, particularly due to particulate matter exposure [1].

Fine particles generated during combustion may penetrate deeply into the respiratory system and contribute to asthma, chronic obstructive pulmonary disease, cardiovascular disease, and lung cancer [7]. Sensitive population groups include children, elderly individuals, and people with preexisting respiratory diseases.

Molnár et al. [2] emphasized that indoor exposure to combustion generated particles from residential wood burning may contribute significantly to total personal expo-

sure, particularly during periods of active stove operation. The study highlighted that pollutant accumulation indoors may become substantial when ventilation conditions are insufficient or when pollutant removal is limited.

The SMHI population exposure assessment and the IVL report both identify $\text{PM}_{2.5}$ exposure as an important contributor to premature mortality in Sweden [8], [13]. Long term exposure to combustion-related particles therefore remains a significant public health concern.

In addition to long term effects, short term exposure to elevated smoke and combustion gases may result in coughing, throat irritation, dizziness, headaches, breathing discomfort, and eye irritation. The FETA indoor air quality fact sheet further notes that indoor pollutant exposure may increase considerably in poorly ventilated spaces or when leakage occurs through stove and chimney systems [9].

The recent scientific reports study similarly emphasized that indoor exposure to combustion generated ultrafine particles and gases may increase substantially during stove operation, especially under unfavorable ventilation conditions [3].

2.8 Relevance to the Present Study

The reviewed literature demonstrates that wood stove emissions and indoor pollutant exposure are strongly influenced by combustion conditions, airflow behavior, chimney draft, and pressure balance within the room. Incomplete combustion resulting from insufficient airflow may increase emissions of particulate matter and carbon monoxide, while underpressure conditions may contribute to leakage and reverse airflow through chimney systems.

Previous studies have shown that ultrafine particle concentrations may increase significantly near stove joints, smoke pipe interfaces, and leakage locations, particularly during ignition and unstable combustion conditions [2], [3], [10]. These findings are directly relevant to the present study, where mobile and stationary particle measurements were conducted to identify pollutant distribution and leakage behavior.

The literature also highlights the importance of sufficient combustion air supply and stable pressure conditions for maintaining proper combustion and reducing indoor pollutant exposure. These concepts form the theoretical basis for the present experimental investigation of airflow conditions, chimney leakage, pressure behavior, and pollutant transport associated with temporary wood stove operation.

3

Equipments

Table 3.1: Measurement instruments and parameters used in the experimental setup

Device	Quantity	Measurement	Unit
Testo Thermocouple Temperature Sensor	2	Temperature	°C
Testo 174H Temperature Logger	4	Temperature, Relative Humidity	°C, % RH
Rotronic CP11 CO ₂ Meter	1	Temperature	°C
TSI P-Trak UPC	2	Ultrafine particles (UFP)	pt/cc
Brüel & Kjær Multi-Gas Monitor	1	CO ₂ , CO, TOC	ppm
DustTrak DRX Aerosol Monitor	1	PM ₁ , PM _{2.5} , PM ₁₀	µg/m ³
Air Flow Rate Control Unit	1	Extract fan, Air flow rate	m/s
Swema 300 Differential pressure Measurement device	1	ΔP pressure	Pa
Delta Ohm HD32.2 Globe temperature sensor	1	T_g , T_{room}	°C

This chapter presents a detailed description of the equipment used in this study to evaluate the performance of the FirePipe emergency stove under real indoor environmental conditions. As discussed in the previous chapter, the primary objective of this research is to investigate the interaction between the stove and indoor environmental parameters, particularly temperature distribution, indoor air quality, and pressure behavior during operation in winter conditions.

To achieve this objective, a range of specialized measurement instruments was employed which is shown in the table 3.1. These instruments were used to monitor key environmental parameters, including indoor air temperature, concentrations of pollutants such as carbon monoxide (CO), carbon dioxide (CO₂), particulate matter (PM_{2.5} and PM₁₀), ultrafine particles (UFP), as well as differential pressure between the indoor and outdoor environment. These measurements form the basis for evaluating both the performance and safety of the stove.

3.1 TSI P-Trak Ultrafine Particle Counter (UPC)

3.1.1 Instrument Description

The TSI P-Trak Ultrafine Particle Counter (UPC) is a portable instrument used to measure the concentration of ultrafine particles (UFPs) in air. It is based on condensation particle counter (CPC) technology, which allows the detection of particles that are too small to be measured using standard optical instruments.

In this study, the P-Trak is used to monitor particle emissions generated during the operation of the FirePipe stove, particularly during phases such as ignition and refuelling.

3.1.2 Measured Parameter and Units

The P-Trak measures the number concentration of airborne particles within a size range of approximately 20 nm to 1 μm . Instead of measuring mass, it counts the number of particles present in the air, which is especially useful for detecting very small particles produced during combustion.

The results are expressed in particles per cubic centimeter ($\text{particles}/\text{cm}^3$), which represents the number of particles present in a small volume of air. This allows the variation in particle concentration to be observed over time.



Figure 3.1: TSI P-Trak Ultrafine Particle Counter

3.1.3 Measurement Principle

The P-Trak operates using a method that allows very small particles to be detected by first increasing their size before measurement. This is achieved through a process involving vapor condensation.

Air is first drawn into the instrument using an internal pump. The sampled air is then exposed to a vapor, which mixes with the air under controlled temperature conditions. As the air moves into a cooler region inside the instrument, the vapor condenses onto the particles present in the air.

This condensation causes the particles to grow into larger droplets. Once enlarged, these droplets pass through a light beam, where each particle scatters light. The instrument detects these light signals and counts them individually.

By counting each detected particle, the instrument determines the total particle concentration in the sampled air. This method makes it possible to measure ultra-fine particles that would otherwise be too small to detect.

3.1.4 Application in this thesis study

In this study, the P-Trak (figure: 3.1) is used to evaluate indoor air quality during the operation of the FirePipe stove under real winter conditions. It is particularly useful for identifying changes in particle concentration during different stages of stove operation, such as ignition, steady combustion, and refuelling.

Since combustion processes generate a large number of very small particles, monitoring ultrafine particle concentration is important for understanding the impact of the stove on indoor air quality.

Ultrafine particles are of concern because they can enter deep into the respiratory system and may have negative health effects. Therefore, measuring their concentration provides important information for assessing both the performance and safety of the stove.

3.2 Brüel & Kjær Multi-Gas Monitor

3.2.1 Instrument Description

The Brüel & Kjær Multi-Gas Monitor is a measurement instrument used to detect and quantify different gases present in air. It is designed for applications where several gases need to be monitored simultaneously with high accuracy.

In this study, the instrument is used to measure gaseous emissions produced during the operation of the FirePipe stove. These measurements are important for evaluating indoor air quality under realistic conditions.



Figure 3.2: Brüel & Kjær Multi-Gas Monitor

3.2.2 Measured Parameter and Units

The instrument measures the concentration of selected gases present in the air sample. These typically include combustion-related gases such as carbon monoxide (CO), carbon dioxide (CO₂), and in some cases volatile organic compounds (VOCs), depending on the configuration of the instrument.

Gas concentrations are commonly expressed in parts per million (ppm), which indicates the number of gas molecules present per million parts of air. This unit is widely used in air quality studies and allows easy comparison of concentration levels.

3.2.3 Measurement Principle

The Brüel & Kjær Multi-Gas Monitor operates using a photoacoustic detection method based on infrared radiation. This method allows different gases to be identified and measured based on how they interact with light.

Air is first drawn into a sealed measurement chamber inside the instrument. The sample is then exposed to infrared light at specific wavelengths. Each gas absorbs light differently depending on its molecular structure.

Inside the instrument, a rotating system selects different optical filters, each corresponding to a specific gas. As the filtered light passes through the air sample, only the gases that match the selected wavelength absorb energy.

This absorption causes a small increase in temperature and pressure within the chamber, which produces a sound wave. Sensitive microphones inside the instru-

ment detect this sound signal. The strength of the signal is directly related to the concentration of the gas present.

By repeating this process for different filters in sequence, the instrument can measure multiple gases from the same air sample with good accuracy.

3.2.4 Application in this thesis study

In this study, the Brüel & Kjær Multi-Gas Monitor (figure: 3.2) is used to assess indoor air quality during the operation of the FirePipe stove. The focus is on measuring gases produced during combustion, particularly carbon monoxide and carbon dioxide.

Carbon monoxide is a toxic gas that can pose serious health risks even at low concentrations, while carbon dioxide is used as an indicator of ventilation conditions and combustion efficiency.

The ability of the instrument to measure multiple gases in real time makes it suitable for capturing changes in air quality during different phases of stove operation, such as ignition, steady burning, and refueling. These measurements provide essential information for evaluating both the performance and safety of the stove.

3.3 DustTrak DRX Aerosol Monitor

3.3.1 Instrument Description

The DustTrak DRX Aerosol Monitor is used to measure the concentration of airborne particles of different sizes in real time. This makes it suitable for indoor air quality studies.

In this study, the instrument is used to quantify particulate emissions generated during the operation of the FirePipe stove.

3.3.2 Measured Parameter and Units

The DustTrak DRX measures particulate matter across different size fractions, including PM_1 , $PM_{2.5}$, PM_{10} , and total suspended particles. These categories represent particles of different sizes present in the air.

The measured concentrations are expressed in milligrams per cubic meter (mg/m^3), which represents the mass of particles in a given volume of air. The instrument is capable of measuring both low and high particle concentrations. The instrument provides data with high precision, but the absolute concentration may be strongly overestimated. There are studies that indicate that the readings of the DustTrak overestimate $PM_{2.5}$ concentrations by a factor between 2 and 4 compared correct reference instruments [14]. Although the instrument provides just a rough estimation of the concentration level, it is a good tool for studying trends and temporal

variations.

3.3.3 Measurement Principle

The working principle of the instrument is based on light scattering. Air is drawn into the instrument and directed into a measurement chamber.

Inside the chamber, a laser beam passes through the air sample. As particles move through the beam, they scatter the light. The amount of scattered light depends on the size and number of particles present.

A photodetector captures the scattered light and converts it into an electrical signal. This signal is then processed to estimate the particle concentration.

The instrument provides continuous measurements across different particle size ranges, allowing changes in particle levels to be observed over time.



Figure 3.3: DustTrak DRX Aerosol Monitor

3.3.4 Application in this thesis study

In this study, the DustTrak (figure: 3.3) is used to monitor particulate matter during different phases of stove operation, including ignition, steady burning, and refueling, under real indoor conditions.

Since combustion processes produce particles of different sizes, monitoring particulate matter is important for understanding the impact of the stove on indoor air quality.

The data obtained from the instrument is used to identify variations in particle concentration and to assess potential health risks associated with exposure to fine particles.

3.4 Testo 174H Temperature Logger

3.4.1 Instrument Description

The Testo 174H is a compact data logger used to measure and record indoor temperature over time. It is commonly used in indoor environmental studies where continuous monitoring of temperature is required.

In this study, the instrument is used to track temperature variations during the operation of the FirePipe stove.



Figure 3.4: Testo 174H Temperature Logger

3.4.2 Measured Parameter and Units

The Testo 174H measures air temperature, which is expressed in degrees Celsius (°C).

Temperature is an important parameter in this study, as it helps evaluate the heating performance of the stove and the distribution of heat within the indoor space.

3.4.3 Measurement Principle

The instrument measures temperature using a built-in sensor that responds to changes in thermal conditions. As the temperature changes, the electrical properties of the sensor vary, and this change is converted into a temperature value.

The device records temperature at regular time intervals, allowing continuous monitoring over the duration of the experiment.

3.4.4 Application in this thesis study

In this study, the Testo 174H (figure: 3.4) is used to monitor indoor temperature during different stages of FirePipe stove operation, including ignition, steady burning, and refueling.

The recorded data is used to evaluate how effectively the stove increases and maintains indoor temperature under real operating conditions. It also helps in understanding temperature variations within the room during the experiment.

Multiple Testo sensors were placed at different locations to capture temperature distribution.

3.5 Testo Thermocouple Temperature Sensor

3.5.1 Instrument Description

A thermocouple is a device used to measure temperature at a particular point by directly sensing thermal conditions. It is commonly selected in experimental work because it can handle a wide range of temperatures and respond quickly to changes

In this study, thermocouples are connected to a data logging system to record temperature at different locations within the test setup.

3.5.2 Measured Parameter and Units

The thermocouple measures temperature, which is reported in degrees Celsius ($^{\circ}\text{C}$). Temperature measurements are essential in this study as they provide information about how heat from the FirePipe stove spreads within the indoor environment.

3.5.3 Measurement Principle

The thermocouple works based on the generation of a small electrical signal when two different metals (here nickel and chromium) are joined and exposed to heat.

It consists of two metal wires made from different materials that are connected at one end. When this junction is exposed to a temperature different from the

other end, a voltage is produced. This voltage is measured by the data logger and converted into a temperature value.



Figure 3.5: Thermocouple Temperature Sensor

3.5.4 Application in this thesis study

In this study, a thermocouple system with four measurement nodes (figure: 3.5) is used to monitor temperature at specific locations within the room. These Each node records temperature directly at its position, allowing detailed observation of temperature variations.

Measurements are taken during different stages of stove operation, including ignition, steady burning, and refuelling. This makes it possible to analyze how heat is distributed throughout the indoor space.

The collected data is used to evaluate the heating performance of the FirePipe stove and to study temperature differences within the environment.

3.6 Delta Ohm HD32.2 Globe Temperature Sensor

3.6.1 Instrument Description

The Delta Ohm HD32.2 is a thermal microclimate data logger used to measure environmental conditions related to heat exposure and thermal comfort. The instrument

is equipped with multiple sensors, including a globe thermometer, air temperature probe, and humidity sensor.

In this study, the instrument is used to assess the thermal environment in the room during the operation of the FirePipe stove.

3.6.2 Measured Parameter and Units

The instrument measures several thermal parameters, including air temperature, room temperature, globe temperature, and relative humidity. In this study, particular focus is given to globe temperature.

Globe temperature is expressed in degrees Celsius ($^{\circ}\text{C}$) and represents the combined influence of air temperature and radiant heat from surrounding surfaces.

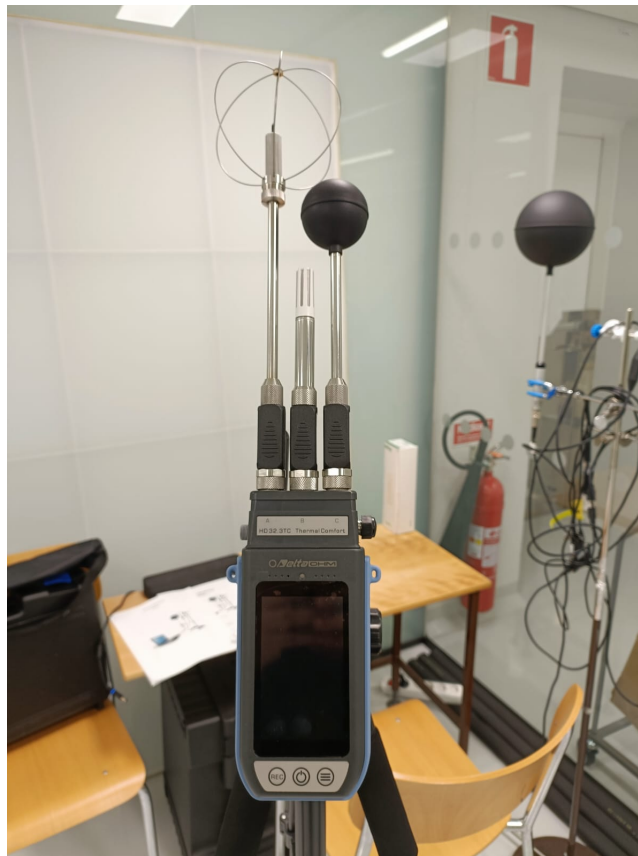


Figure 3.6: Globe Temperature Sensor

3.6.3 Measurement Principle

The globe temperature is measured using a sensor placed inside a hollow black sphere. The surface of the sphere absorbs heat from the environment, including both air temperature and radiation from nearby objects.

As the sphere absorbs heat, its temperature changes, and this is recorded by the

internal sensor. The measured value reflects the overall thermal conditions at that location. Since the measurement accounts for both convection and radiation, it provides a more representative indication of the thermal environment compared to air temperature alone.

It also utilizes the measured air temperature and globe temperature to calculate operative temperature which is also used for our studies. Operative temperature is a commonly used thermal comfort parameter that combines the effects of convective heat transfer and radiant heat exchange into a single value. This provides a more comprehensive indication of perceived indoor thermal conditions than air temperature alone.

3.6.4 Application in this thesis study

In this study, the Delta Ohm HD32.2 (figure: 3.6) is used to monitor the thermal environment during the different phases of FirePipe stove operation: ignition, steady burning, and refueling.

The instrument is positioned at a fixed location within the room to capture the influence of heat emitted from the stove. Data from globe temperature measurements are used to understand how heat is distributed within indoor spaces and to evaluate thermal comfort conditions under real operating conditions.

3.7 Rotronic CP11 CO₂ Meter

3.7.1 Instrument Description

The Rotronic CP11 is a portable instrument used to measure carbon dioxide (CO₂) concentration in indoor environments. It is commonly used in air quality studies to assess ventilation conditions and the presence of indoor pollutants. In this study, the instrument is used to monitor CO₂ levels and relative humidity during the operation of the FirePipe stove.

3.7.2 Measured Parameter and Units

The instrument Rotronic CP11 measures the concentration of carbon dioxide (CO₂) in air. The measured values are expressed in parts per million (ppm), which indicates the amount of CO₂ present in a given volume of air. CO₂ concentration is an important parameter in this study, as it provides information about ventilation conditions and combustion behavior.

3.7.3 Measurement Principle

The Rotronic CP11 measures CO₂ concentration using an infrared based sensing method. Air enters the sensor chamber, where it is exposed to infrared light. CO₂ molecules absorb infrared radiation at specific wavelengths. The instrument detects the reduction in light intensity caused by this absorption and uses it to determine

the concentration of CO₂ in the air. This method enables reliable, continuous measurement of CO₂ levels in indoor environments.



Figure 3.7: Rotronic CP11 CO₂ Meter

3.7.4 Application in this thesis study

In this study, the Rotronic CP11 (figure: 3.7) is used to evaluate indoor air quality during the different phases of FirePipe stove operation ignition, steady burning, and refueling. The instrument is placed within the room to monitor changes in CO₂ concentration over time. The collected data is used to assess ventilation effectiveness and to understand how the stove operation influences indoor air quality under real conditions.

3.8 Swema 3000 Differential Pressure Instrument

3.8.1 Instrument Description

The Swema 3000 is a portable instrument used to measure differential pressure and airflow in indoor environments. It is commonly applied in ventilation studies to evaluate pressure conditions and air movement. In this study, the instrument is used together with leakage testing accessories to monitor pressure conditions inside the room during the experiments.

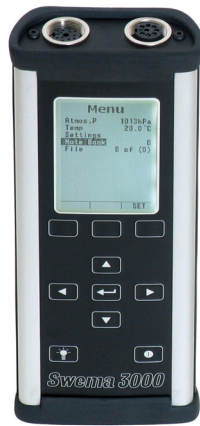


Figure 3.8: Differential Pressure Instrument-Swema 3000

3.8.2 Measured Parameter and Units

The instrument measures differential pressure (ΔP), which is expressed in Pascals (Pa). Differential pressure is an important parameter in this study, as it provides information about airflow behaviour and ventilation performance under different operating conditions.

3.8.3 Measurement Principle

The Swema 3000 operates using pressure sensors that detect the difference in air pressure between two points. Each measurement point is connected to the instrument using flexible silicone tubes, which transmit the air pressure from the selected locations to the device. The instrument then measures the pressure difference and converts it into an electrical signal, which is displayed as a pressure value.

3.8.4 Application in this thesis study

In this study, the differential pressure instrument swema 3000 (figure: 3.8) is used to monitor room pressure during different test conditions, including normal operation, high airflow, and critical pressure scenarios. These measurements are used to analyse how pressure variations influence airflow behaviour and their effect on ultrafine particle concentrations within the indoor environment. The measured pressure difference was used together with a fixed airflow measurement device installed in the ventilation duct to determine the airflow rate during the experiments.

4

Experiment Background

The experimental study was conducted at the training facility of Södra Älvsborgs Räddningstjänstförbund located in Borås. This location was selected primarily due to safety considerations, as the nature of the experiment involves combustion processes and the potential release of indoor air pollutants. Conducting such an experiment in an occupied residential apartment would pose significant health and safety risks to occupants. Therefore, a controlled training environment designed for fire related activities was deemed the most appropriate and secure setting for this investigation.



Figure 4.1: Södra Älvsborgs Räddningstjänstförbund - Fire Fighters Training Center

The experimental activities were carried out over multiple days, beginning with initial setup on March 3rd, followed by detailed experimental measurements conducted

4. Experiment Background

on March 4th and March 5th. The first day involved preparation, assembly, and arrangement of the experimental setup, while the subsequent days were dedicated to data collection under controlled conditions.

The experiments were conducted within a small, house like test structure located at the training facility. A comprehensive representation of the test environment is provided through floor plans shown in figure: 4.3 and external views, including front and rear perspectives of the structure as shown in figure: 4.2.



Figure 4.2: Views of the experimental building environment: Top-left shows the left side view of the building, top-right shows the right side view, and the bottom image shows the front side view of the building.

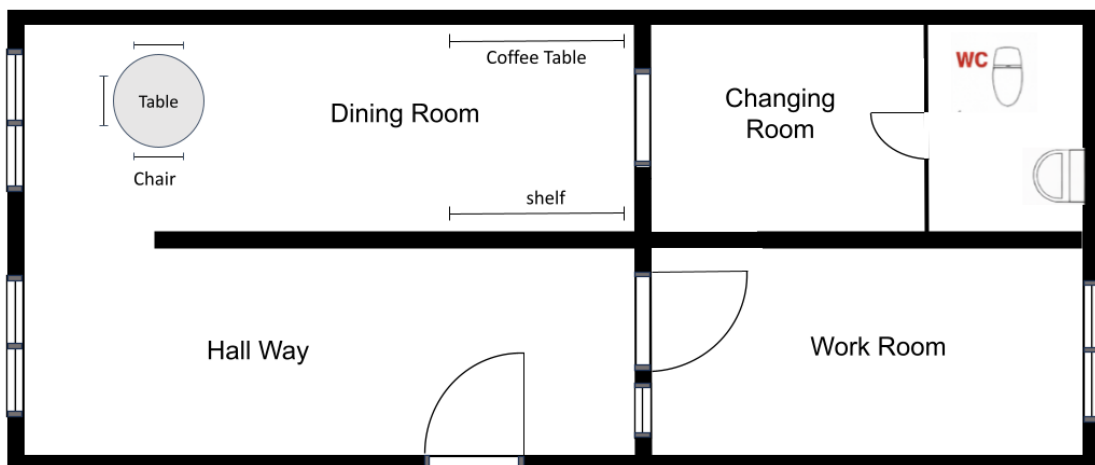


Figure 4.3: Floor plan of the Experimental Building

For the purpose of this study, only a single work room within the structure was considered, as the experimental focus was on the operation of the stove within an enclosed indoor space. The layout and dimensions of the room are illustrated in the upcoming sections.

5

Methodology

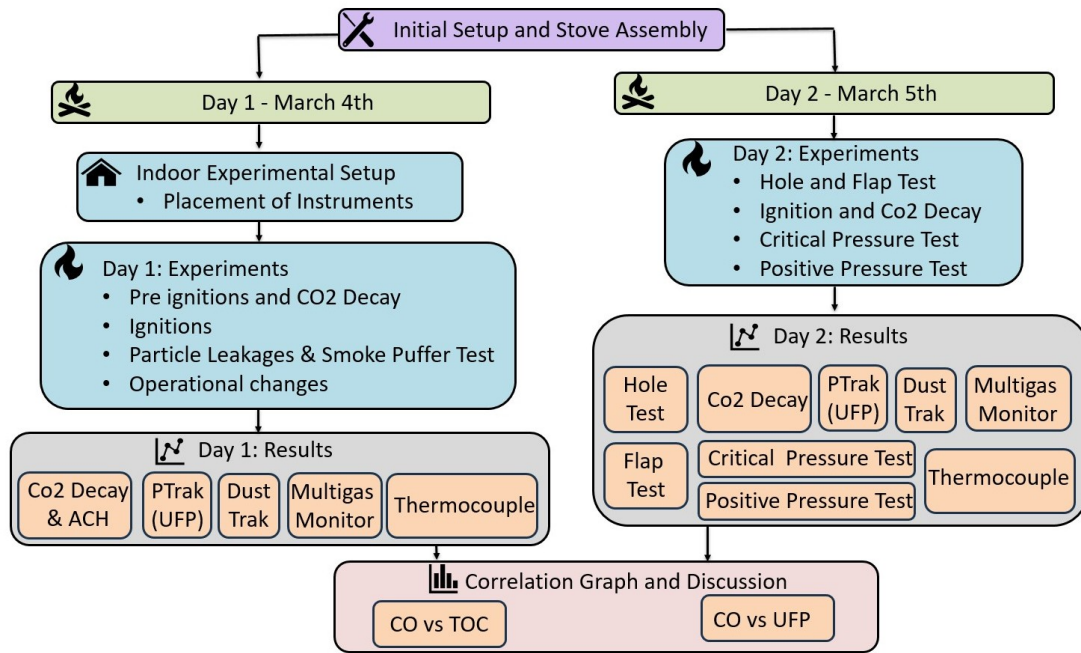


Figure 5.1: Methodology

5.1 Initial Setup - March 3rd

The experimental setup commenced on March 3rd at the fire fighter training center (Södra Älvsborgs Räddningstjänstförbund) in Borås, where all required equipment and materials were transported and arranged. Upon arrival, preparations included organizing the stove components, instrumentation, and supporting materials.

The stove, delivered in sheet form as shown in figure 5.2, was assembled on-site in accordance with the manufacturer's instruction manual provided by the FirePipe company. The assembly process involved the use of basic tools such as a hammer, gloves, and a stone, which are recommended for proper handling and fitting of the components. Therefore, while the stove is designed for relatively simple assembly, it cannot be considered entirely tool free.

All components of the stove are manufactured from carbon steel sheets, which are

provided with a protective oil coating. These sheets contain pre cut lines that allow them to be bent or folded to form the required stove components during assembly. Due to the material properties of carbon steel, the components are susceptible to corrosion when exposed to moisture or condensation. Consequently, it is recommended that the stove be used and stored in a dry environment to prevent rust formation. For safe operation, the stove must be placed on a non-combustible base.

5.1.1 Stove Assembly

The assembly process required approximately 3.5 hours and was intentionally carried out under conditions simulating a real life scenario. Specifically, the installation was performed, with assistance representing a typical user with limited technical expertise.

Throughout the assembly, systematic observations were recorded. Particular attention was given to identifying challenges, defects, and usability issues that an untrained individual might encounter. These observations later informed recommendations for design and usability improvements.

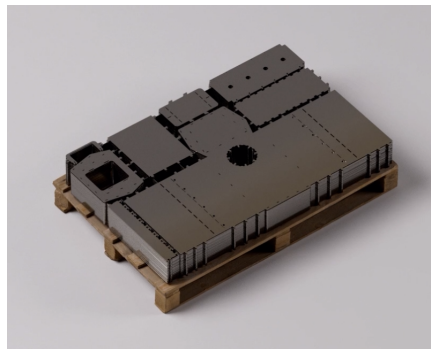


Figure 5.2: Stove In-sheet Form

5.1.2 Observations During Stove Assembly



Figure 5.3: Some of the components of the stove during assembly

During the assembly process, several practical issues were identified. One notable concern was an error in the instruction manual, where a component was incorrectly labelled. This discrepancy has been communicated to the manufacturer for clarification.

In terms of handling, certain components were relatively straightforward to assemble using basic tools such as a hammer. However, other parts proved difficult to manage individually and required assistance. Gaps were observed between joined components, even after following the recommended procedure of hammering the joints. In some instances, these gaps could not be fully eliminated, potentially affecting both structural integrity and sealing performance.

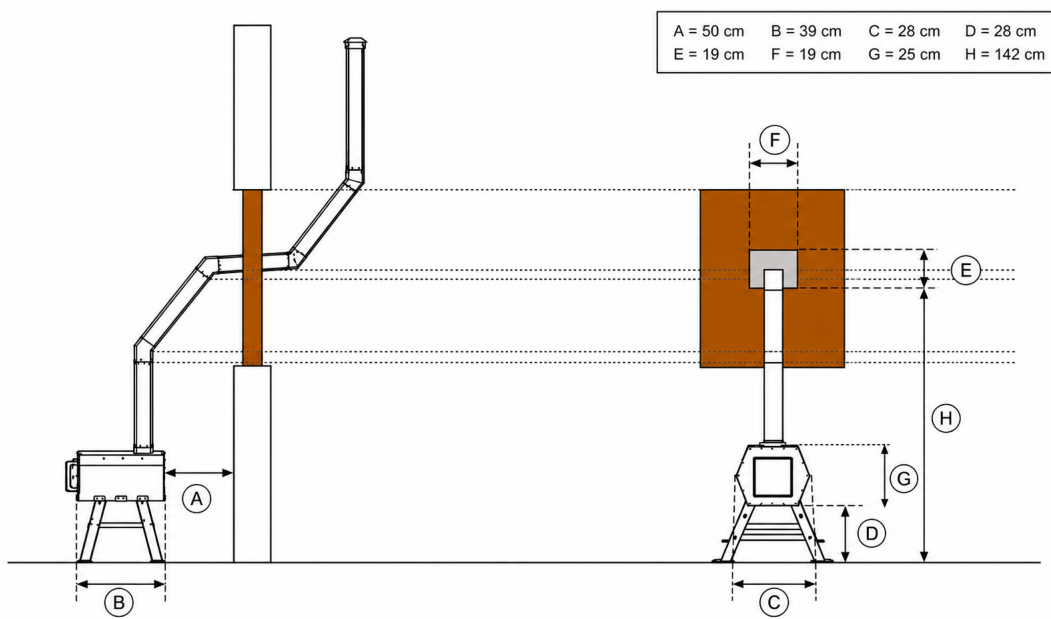


Figure 5.4: Complete visualization of Stove assembly

Additionally, the hook mechanisms used to connect sheet components were found to be relatively weak. Repeated adjustments reduced their rigidity, indicating potential limitations in material quality or design. Furthermore, alignment issues were noted at certain edges, where adjoining sheets did not fit together properly. These inconsistencies made the assembly process more complex and may pose challenges for untrained users.

Following communication with the manufacturer, it was explained that the stove is not intended to be assembled independently by a single user. Instead, in emergency scenarios such as war or crisis situations, the intended mode of deployment involves collective assembly. Temporary community setups are expected to be established within local areas, where individuals can collaborate and assist one another in assembling the stoves. It is designed for collective installation in emergency scenarios, where community based assembly is expected. From this perspective, several of the observed handling challenges may be mitigated through collaborative effort.

It was also emphasized that certain components, which required manual bending, were more challenging to manipulate, but this thickness of the metal sheet is essential for maintaining structural integrity and cannot be simplified without compromising performance.

5.1.3 Chimney Installation Challenges

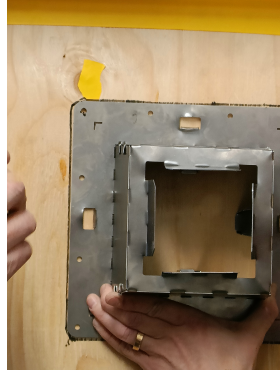


Figure 5.5: L-shaped opening on the corners of the chimney attachment

During the installation of the chimney into a wooden board on the window as shown in the figure 5.5, practical difficulties were encountered. Specifically, marking the required L-shaped opening proved challenging due to limited accessibility. The opening was too small to allow a marker to pass through, making accurate marking difficult.

This issue was further complicated by folds behind the fitting plate, which created a gap between the plate and the board surface. As a result, achieving precise markings prior to drilling was difficult. This aspect of the design may benefit from improvement to facilitate easier and more accurate installation.

5.1.4 Installation Procedure and Modifications



Figure 5.6: Stove assembly views: Left shows the stove side view and right shows the stove front view.

Following the assembly of all components, the stove comprising the combustion chamber refer to figure 5.6, and chimney was assembled outdoors before being installed indoors.

According to the instruction manual, the chimney components should be mounted onto the window board prior to installing the board onto the window as shown in figure 5.7, after which the system is assembled from inside the room. However, due to spatial constraints within the room, this procedure was not feasible. Instead, a modified approach was adopted in which the window board was installed first, followed by attachment of the chimney components. This method proved more practical under the given conditions. Once all components were assembled, the stove was prepared for operation.



Figure 5.7: Chimney installation and components: The left shows the stove with the chimney mounted to the window board, and the right shows the chimney components.

5.2 Day 1 - March 4th

5.2.1 Initial Conditioning



Figure 5.8: Outdoor burn OFF of residual oil.

Although the stove assembly was completed on March 3rd, the initial oiling and firing process was conducted on March 4th. This step was necessary to burn off residual manufacturing substances and stabilize the system prior to experimentation. Birch wood was used as a fuel and had a moisture content of 18 %. During this initial firing, measurements were recorded using instruments positioned near the stove outdoors.

5.2.2 Indoor Experimental Setup

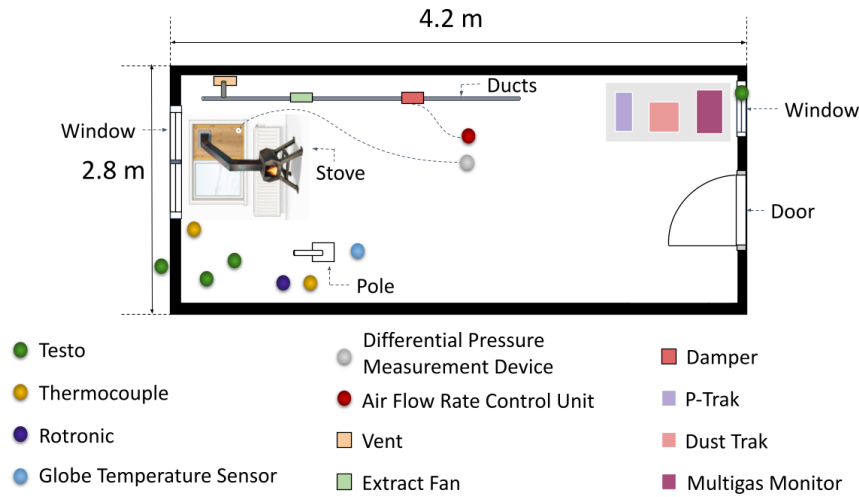


Figure 5.9: Floor plan of the experimental room illustrating the designated positions of all instruments, with each location corresponding to the colour and shape coding shown in the figure.



Figure 5.10: Interior view of the experimental setup showing the stove mounted onto the window board, with the chimney passing through the board. The ducting system is positioned to the right of the stove, while the extract fan is located below the duct and connected to a damper positioned in front of the fan. The measurement instruments placed on the table are also visible in the figure.

The indoor experimental setup consisted of a controlled room environment equipped with a system. The firepipe stove was mounted onto the gypsum board and was installed on the window. The main duct connected to the external vent was installed and monitored from inside the room. An extract fan was positioned below the duct and fitted with a damper for airflow regulation, as shown in the figure 5.10. All the stationary instruments placed on the table sampled air from the farthest left end of the table.

5.2.2.1 Purpose of the Extract Fan

An extract fan system equipped with ducts and a damper was employed as part of the experimental setup. It is important to note that this system was not intended to represent conventional mechanical ventilation. In real life applications, particularly in emergency or crisis scenarios such as war or power outages, the use of mechanical ventilation systems cannot be assumed. Under such conditions, indoor environments are instead influenced primarily by external factors, most notably wind.

Wind can significantly affect indoor pressure conditions by creating either under-pressure or overpressure within a space. These pressure variations influence airflow patterns, alter the direction of air movement, and directly affect the performance of combustion systems such as stoves and their associated chimney draft. Therefore, in order to study the behaviour of the stove under conditions that are more representative of real world scenarios, it was necessary to introduce a controlled method of simulating these external influences.

The extract fan was thus used as a means to generate controlled airflow and pressure conditions within the room, allowing the simulation of wind induced effects in a repeatable and measurable manner. This approach made it possible to systematically vary and maintain specific pressure conditions, thereby enabling the investigation of how the stove responds to different airflow environments. This setup also allowed for the assessment of the sensitivity of the stove to pressure variations.

Furthermore, provides better clarity about the conditons under which the stove is safe to use and the use of the extract fan enabled the identification of potential failure conditions of the stove system. By simulating adverse airflow scenarios, it was possible to observe how the system behaves under non ideal conditions that may occur in practice. This is particularly important from a safety perspective, as improper airflow can lead to the release of combustion products into the indoor environment.

Overall, the use of the extract fan provided a controlled yet realistic framework for evaluating stove performance under varying pressure conditions, thereby ensuring that the experimental findings are relevant to practical applications where external airflow influences cannot be neglected.

5.2.2.2 Placement of instruments

With respect to instrumentation placement refer figure 5.9, careful consideration was given to achieving representative indoor air measurements. The instruments were positioned at approximately breathing height and near the center of the room to capture well mixed air conditions. Although the selected location was not exactly at the geometric center, it was sufficiently central while maintaining distance from the stove to avoid direct influence from convective heat plumes. This placement ensured more reliable and representative readings of indoor air quality.

5.2.2.2.1 Pressure transducer

The differential pressure measurement instrument shown in figure 5.11, also called a pressure transducer, was used to monitor pressure differences between indoor and outdoor environments. To avoid localized disturbances, the indoor outdoor pressure difference was measured near the bottom of the window rather than directly at the chimney opening. The location of the pressure measurement point can be seen on the lower right side of the window board in figure 5.11.



Figure 5.11: View of the tube located at the lower right corner of the window, connected to the pressure transducer for measuring the differential pressure between the indoor environment and the outside.

5.2.2.2.2 Temperature measurement devices - Thermocouples and testo

The stove was installed approximately 50 cm from the wall and securely connected to the chimney using a key which is a small piece of metal used to keep it in place. A total of six electronic measurement systems were used, including two thermocouples and four Testo instruments. Placement of these can also be seen in the floor

plan figure 5.9. A thermal comfort measurement device equipped with a globe thermometer was placed near the stove to monitor operative temperature.

A vertical measurement pole was installed approximately 1 meter from the stove to measure temperature stratification. Thermocouples were positioned at heights starting from 1 meter, with intervals of 0.5 meters, in accordance with ISO 7730, which is shown in figure 5.12.

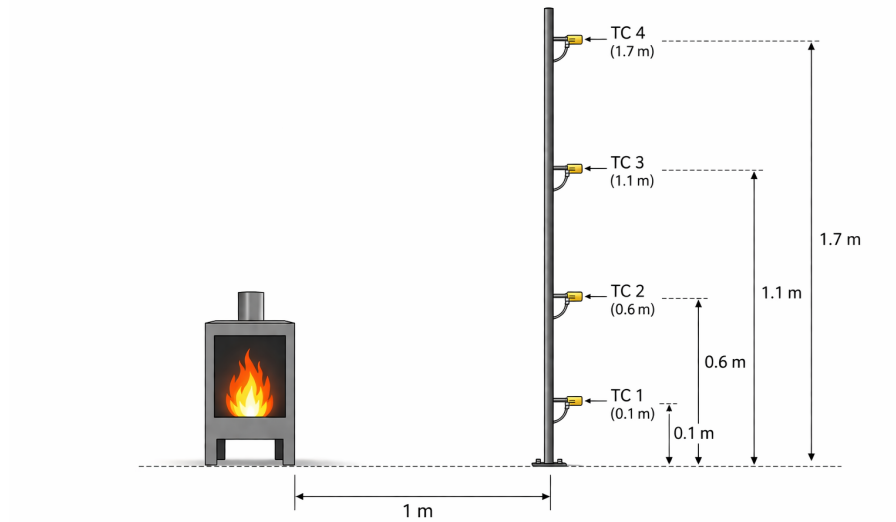


Figure 5.12: Thermocouple mounted on a vertical pole with measurement nodes N1, N2, N3, and N4, positioned in accordance with ISO 7730 guidelines.

A second thermocouple was positioned near the chimney window, as shown in figure 5.13, inside the room to monitor surface temperature variations near the chimney. Additionally, one Testo unit was placed outdoors near the chimney outlet to measure external temperature and relative humidity. For better illustration and understanding, the sensors positions refer to figure 5.9

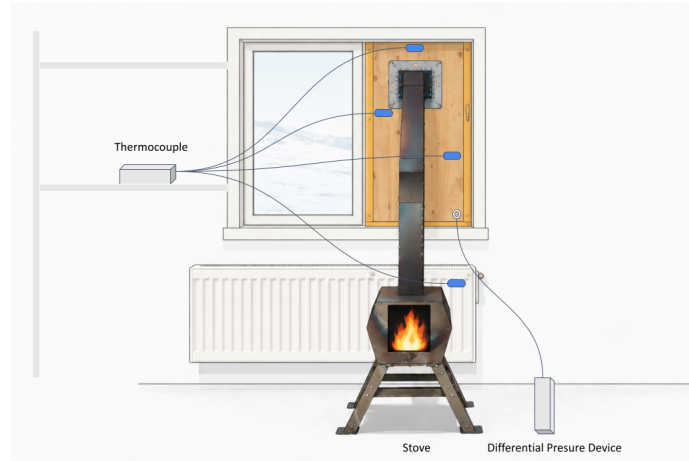


Figure 5.13: Thermocouple attached to the window board behind the stove, with measurement nodes N1, N2, N3, and N4 respectively.

5.2.2.2.3 Control Unit

The extract fan operation was controlled using a dedicated control unit as shown in the figure 5.14, equipped with an EC (electronically commutated) fan. This system allows for precise adjustment of airflow through high and low voltage regulation and is significantly more efficient than conventional transformer based controllers.

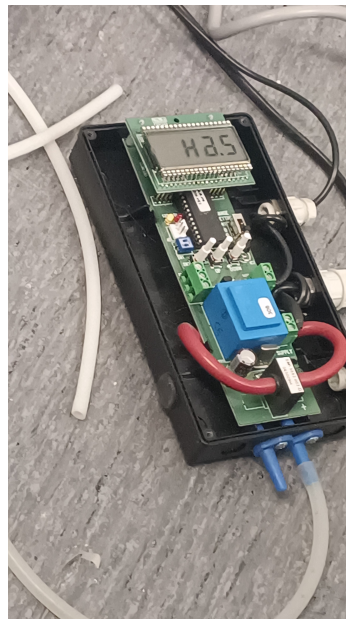


Figure 5.14: Air flow rate Control Unit

5.2.2.2.4 Damper Selection and Sizing

The damper was placed right after the extract fan along the duct to control the flow of air and pressure. To determine an appropriate operating configuration, the damper size was selected based on its influence on flow resistance and the corresponding response of the pressure measurement system. Initially, a larger damper was used, which resulted in higher resistance within the airflow path. During the evaluation of the ventilation system, the pressure measurement system indicated that the resulting pressure differences were either very small or did not reach the intended operating range. In addition, the recorded values exhibited fluctuations, suggesting unstable system behaviour.

Qualitative observations further supported these findings. When assessed manually, only weak suction was detected at the exhaust, and no clear directional airflow within the room could be identified. These observations indicate that the ventilation system was not able to establish a controlled and stable pressure environment. Despite adjustments to the fan settings, the system did not respond as expected, and the desired airflow conditions could not be achieved.

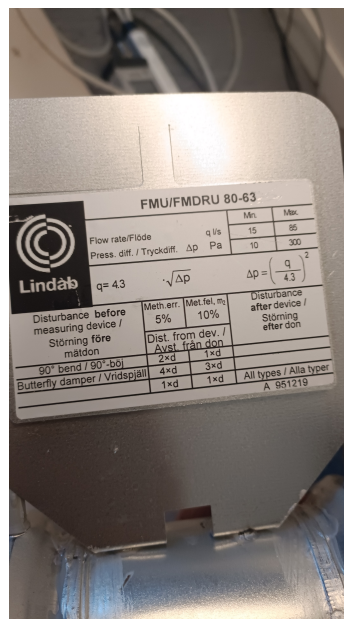


Figure 5.15: Selected damper with its specifications

This behaviour suggests that the system was constrained by excessive resistance within the airflow path, indicating that the selected damper configuration was too restrictive for the given experimental setup. Due to the excessive resistance and the limitations of the system in achieving the desired airflow conditions, this configuration was deemed unsuitable.

From the specifications shown in the figure 5.15, the selected (smaller) damper operates at $Q = 4.3$. This value represents a level of resistance that results in a

minimum achievable airflow rate of approximately 15 L/s and a corresponding minimum pressure of around 10 Pa. Therefore, the smaller damper was selected as it provided a more suitable and achievable operating range for the given experimental conditions.

The positions of the other instruments can be seen on the figure given above 5.9. All measurements were recorded continuously at predefined time intervals, which are attached in the equipment section.

5.2.3 Pre-ignition and CO₂ decay

Prior to ignition, the ventilation system was set to an $Q=4.3$ airflow rate of 11 L/s. Under these conditions, the room exhibited a negative pressure of approximately -4.9 Pa. This shows that the room is in underpressure.

At 11:42 a.m. on March 4th, a tracer gas test was conducted using a fire extinguisher. A fan was used to ensure uniform distribution, after which the room was sealed and left unoccupied. The decay of CO₂ concentration was monitored to assess ventilation performance.

5.2.3.1 CO₂ Decay Measurement and Air Change Rate (ACH)

The air change rate (ACH) is defined as the number of times the air within a given volume is replaced with fresh air over a specified period of time. It is typically expressed in units of h^{-1} (per hour) and represents a key parameter for quantifying ventilation performance within an enclosed space. In the context of this study, ACH is an essential parameter for understanding indoor air quality, particularly with respect to pollutants. The concentration and removal of these pollutants are strongly influenced by the ventilation rate. Under emergency conditions, such as crisis or war scenarios, mechanical ventilation systems may not be operational. Therefore, ventilation performance cannot be reliably estimated using standard design values or assumptions and must instead be determined experimentally.

To determine ACH, the CO₂ decay method was employed. CO₂ decay refers to the Passive (natural) reduction in CO₂ concentration over time which provides a measure of how quickly air is exchanged within the room. The primary purpose of conducting the CO₂ decay test is to assess the ventilation effectiveness and determine whether indoor pollutant concentrations can be maintained within acceptable limits.

Since pollutants such as CO and UFPs exhibit similar dispersion and removal behaviour to CO₂, the decay rate of CO₂ can be used as an indicator of the removal rate of these pollutants. Therefore, CO₂ serves as a suitable proxy for evaluating overall air exchange performance. A faster decay corresponds to higher ventilation effectiveness, whereas a slower decay indicates poor air exchange and potential accumulation of pollutants. Similarly, a low ACH indicates that pollutants may accumulate within the space, leading to potential health and safety risks. Conversely, a higher ACH suggests effective air circulation and pollutant removal, which is critical

for safe operation of the indoor stove and associated chimney system.

5.2.3.2 Regression Analysis (Stove Switched Off)

The primary purpose of performing regression analysis on the CO₂ decay data is to quantify the decrease in CO₂ concentration over time. Since the CO₂ decay curve may contain small fluctuations, regression is used to smooth these variations and obtain a clearer trend. This allows for better visualization and interpretation of the ventilation behaviour within the room. In this way, the regression provides a more reliable representation of how ventilation is functioning in practice, rather than focusing on short term fluctuations in the measured data.

5.2.4 Ignition Phase

The ignition phase was conducted to evaluate the initial performance of the stove under controlled ventilation conditions and to observe the interaction between combustion, indoor pressure, and air quality. This phase represents a transient condition during which combustion is unstable, and pollutant emissions are typically at their highest.

At the start of ignition, the ventilation system was maintained at the same settings established prior to combustion. These baseline conditions included the fixed fan and damper settings, which defined the airflow rate within the room. The room remained sealed, with all openings closed, in order to maintain controlled and repeatable conditions. The stove was loaded with firewood and ignited with the hatch initially kept closed, representing a typical initial operating condition.

Maintaining constant ventilation conditions was essential to ensure experimental control. By keeping the ventilation parameters unchanged, any variations observed in pressure, combustion behaviour, or pollutant concentrations could be attributed solely to the operation of the stove, rather than to external changes in airflow or system configuration. This approach enabled isolation of the stove's influence on the indoor environment.

Under these conditions, combustion was not properly sustained. To improve combustion conditions, the stove hatch was opened, allowing additional air to enter the combustion chamber. This adjustment led to a visible improvement in flame stability.

Due to the elevated levels of ultrafine particles and carbon monoxide, it became necessary to temporarily modify the conditions for safety reasons. The room and the combustion chamber (hatch) was opened to improve ventilation. The ventilation rate was also increased by adjusting the extract fan.

Following this short intervention at 15:00 pm, the system was returned to its original configuration by closing the room and resetting the ventilation system to its initial operating conditions. Returning to these baseline conditions enabled the experiment

to proceed toward a steady state operating phase.

5.2.4.1 Particle Distribution and Leakage

Particle concentrations were measured using a mobile P-Trak device, which was moved around different sections of the stove and chimney to capture spatial variations. Additional stationary instruments placed inside the room continuously recorded particle concentration, mass concentration, and gas levels.

5.2.4.2 Smoke puffer test

Smoke visualization revealed important airflow characteristics within the system. The smoke was introduced using a smoke puffer near the joints of the horizontal chimney and the interface between the chimney and the board to study the behaviour of the smoke.

5.2.4.3 System Response to Operational Changes

The system response was investigated by introducing controlled changes to the room conditions, including opening and closing the door, adjusting the extract fan and damper, modifying the window opening, and adding fuel to the stove. These steps were carried out sequentially to understand how ventilation and pressure conditions influence combustion behaviour, airflow direction, and pollutant distribution.

- **Opening door:** The first intervention involved opening the door while maintaining the same control system settings. This step was performed to observe how the system responds to a sudden change in room pressure and air supply.
- **Fuel addition:** Additional logs were introduced into the stove to assess the effect of increased fuel load on combustion stability and emissions.
- **Extract fan OFF:** The extract fan was switched off to evaluate the natural ventilation behaviour of the room in the absence of mechanically induced airflow. This step was carried out to understand how the system performs under conditions where ventilation is driven solely by natural forces, such as buoyancy and infiltration through openings.
- **Damper:** The damper position was then adjusted to examine its influence on airflow resistance and pressure conditions. This was done to demonstrate that controlling airflow resistance can influence pressure balance and reduce undesirable airflow patterns.
- **Window:** The window beside the mounted board was opened and subsequently closed to assess the role of air supply in system performance. This step allowed evaluation of how additional air inlets influence ventilation, pressure stability, and pollutant distribution.

Overall, these steps were carried out to systematically isolate the effects of ventilation parameters on stove operation. The experimental work for Day 1 was completed following the execution of these steps.

5.3 Day 2 - March 5th

5.3.1 Initial Experimental Setup

The experimental procedure was initiated at 09:52 am on March 5th. Initial measurements were conducted outside the test room to verify instrument functionality, perform calibration, and obtain reference readings. External measurements continued until 10:10 am.

Subsequently, the instruments were relocated indoors, and measurements resumed under identical extract conditions, with the airflow rate maintained at 11 L/s. The damper was opened, resulting in an under pressure condition within the room. During this period, the stove remained unlit. An opening was introduced in the wooden board of the window to facilitate the later installation of a flap system. For all subsequent measurements, the room door remained closed to ensure controlled conditions.



Figure 5.16: Opening on the window board below the chimney

5.3.2 Hole/Opening Test

To evaluate the suitability of the opening size in the window board and its influence on room differential pressure, a systematic experimental investigation was

conducted. The objective was to ensure sufficient air exchange between the indoor and outdoor environments and to verify that room pressure could be effectively maintained under the given conditions.

The opening in the window board, with dimensions of 14.2 cm $\times$ 21.5 cm, was initially kept fully exposed without any flap; refer to figure 5.16. The size of the opening was then progressively reduced from fully open (21.5 cm) to completely closed (0 cm), and the corresponding differential pressure values were recorded for each configuration.

These measurements were first carried out at an airflow rate of 11 L/s and subsequently repeated at airflow rates of 20 L/s and 30 L/s using the extract fan and control system, with the stove switched off. The opening was deemed appropriate.

5.3.3 Flap Assessment/Flap Test

A flap was installed over the opening in the window board to regulate airflow and prevent backdraft. The primary purpose of introducing the flap was to provide a control mechanism at the opening, ensuring that airflow remained directed and stable under varying pressure conditions.

In the absence of a flap, airflow could occur in both directions depending on pressure differences, potentially resulting in backdraft. This may lead to unwanted air, including smoke or pollutants from the chimney, reentering the room and increasing indoor pollutant concentrations. The flap was introduced to mitigate this effect by regulating airflow and reducing the likelihood of reverse flow.

The flap functioned as a passive control element, responding autonomously to pressure differences across the opening without external intervention. Its movement was driven by variations in indoor pressure, such as those caused by opening and closing doors, as well as external wind effects acting on the building façade. These factors can introduce sudden pressure fluctuations within the room, potentially disturbing airflow conditions. By opening and closing in response to these variations, the flap contributed to stabilizing airflow and damping sudden inflow or outflow. While the hole/opening test confirmed that pressure stability could be achieved under static conditions, the introduction of the flap enabled evaluation under dynamic conditions.

To evaluate its effectiveness, different flap prototypes were tested. The selection criteria were based on material properties such as weight, flexibility, and response time, particularly the ability of the flap to react quickly and reliably to pressure changes and external wind influences.

5.3.3.1 Testing Procedure

Following the previous test, the dynamic response of the opening was evaluated by repeatedly opening and closing the room and building doors. The temporary paper flap exhibited autonomous movement in response to pressure changes, confirming

its responsiveness to indoor pressure variations.

Four flap prototypes were investigated:

- Prototype 1 (P1): Plastic sheet type 1
- Prototype 2 (P2): Plastic sheet type 2
- Prototype 3 (P3): Laminated photo paper
- Prototype 4 (P4): Plastic sheet type 1 (reduced thickness)



(a) Prototype 1

(b) Prototype 2

Figure 5.17: Images of flap prototypes P1 & P2.



(a) Prototype 3

(b) Prototype 4

Figure 5.18: Images of flap prototypes P3 & P4.

All prototypes were tested under airflow rates 20 L/S, with the stove switched off. The flaps were allowed to operate passively without external interference. Differential pressure measurements were recorded for each configuration.

Prototype 3 (P3), consisting of laminated photo paper, was selected as the most suitable flap material. This selection was primarily based on its performance at an airflow rate of 20 L/s, where it produced the least negative pressure compared to the other prototypes.

5.3.4 Ignition and CO₂ Decay

The stove was ignited at 11:53 am using four small logs. Additional logs were introduced and monitoring continued to observe the impact on indoor air quality.

CO₂ was introduced into the room at 12:16 pm while the stove was in operation, using a fire extinguisher. Since occupants are a primary source of CO₂, the room was vacated prior to the test. The door was then closed, and the decay of CO₂ concentration was monitored.

5.3.5 Critical Pressure Test

The critical pressure test was conducted to determine the pressure limit at which the system begins to exhibit undesirable behaviour, particularly in terms of pollutant release and airflow instability.

During this test, the stove remained in operation, and the extract airflow rate was increased to approximately 30 L/s. The opening in the window board was progressively covered to simulate restricted airflow conditions. Differential pressure and ultrafine particle concentrations were continuously monitored throughout the test. The airflow rate of 30 L/s was selected as it represents the maximum capacity of the system. This condition was used to simulate a worst case scenario enabling identification of the critical pressure.

This test identified -5.8 Pa as the critical pressure threshold, beyond which airflow became unfavorable, and pollutant levels increased.

5.3.6 Positive Pressure Test

The positive pressure test was conducted to simulate conditions that may occur in real life scenarios, particularly due to external wind acting on the building façade, as well as other factors such as door operation and ventilation imbalance.

To create a positive pressure condition, the extract fan was reversed, directing airflow into the room. The airflow rate was increased to approximately 30 L/s, and additional logs were introduced to maintain active combustion. The room was kept relatively closed to observe the effects under controlled conditions.

Under these conditions, smoke and pollutants were observed to spread throughout the room. This behaviour indicates that high airflow combined with positive

pressure conditions reduces the effectiveness of pollutant removal and promotes redistribution of contaminants within the indoor space.

These observations demonstrate that both excessive positive pressure and moderate under pressure conditions can negatively affect system performance. An appropriate balance of pressure conditions is therefore required to ensure effective removal of pollutants and maintain stable indoor air quality.

6

Experimental Results and Analysis

6.1 Experimental Result and Analysis - March 4th

6.1.1 CO₂ Decay Measurement and Air Change Rate (ACH)

In this study, CO₂ was introduced into the room at 11:45 p.m, using a fire extinguisher and used as a tracer gas due to its availability and cost-effectiveness compared to other tracer gases. Typically, occupants are the primary source of CO₂; therefore, the space was vacated prior to conducting the decay test. The door was then closed, and the decay of CO₂ concentration was monitored.

The CO₂ decay test performed on Day 1 resulted in an air change rate (ACH) of $1.91\ h^{-1}$. Based on this value, the corresponding ventilation flow rate was calculated to be $33.7\ m^3/h$. When compared with the requirements specified in the Swedish Building Regulations (BBR), the measured ventilation rate satisfies the minimum ventilation requirements. Further details regarding the CO₂ decay calculation are provided in the appendix.

6.1.2 Combustion Behaviour During Ignition

During the start of the ignition, the combustion was not properly sustained under the initial sealed room conditions. A noticeable back draft of air into the room was observed, indicating insufficient airflow through the combustion chamber. This resulted in incomplete combustion, which was reflected in a rapid increase in pollutant concentrations, particularly carbon monoxide and ultrafine particles. The behaviour suggests that the available air supply was inadequate, resulting in unstable and inefficient combustion. The room remained under negative pressure, and the airflow rate through the extract system was maintained at approximately 10–11 L/s.

To improve combustion conditions, the stove hatch was opened, allowing additional air to enter the combustion chamber. This adjustment led to a visible improvement in flame stability and combustion efficiency. Simultaneously, an increase in the negative pressure within the room was observed.

This response can be explained by the enhanced chimney draft resulting from increased heat generation. As the combustion intensified, the upward flow of hot gases through the chimney increased, which in turn extracted more air from the room. This process strengthened the overall extraction effect of the ventilation system,

thereby increasing the negative pressure. This behaviour demonstrates the strong interaction between combustion and ventilation.

Due to the elevated levels of ultrafine particles and carbon monoxide the room was opened and extract fan increased. This intervention resulted in a rapid decrease in particle concentrations, demonstrating the effectiveness of increased ventilation in removing accumulated pollutants. However, this condition was not maintained, as it deviated from the controlled experimental setup.

6.1.3 Particle Distribution and Leakage



Figure 6.1: Chimney components where ultrafine particle (UFP) measurements were conducted: The left shows the horizontal chimney component, The centre shows the angled chimney component, And right shows the vertical chimney component.

The P-Trak measurements presented in figure 6.2 shows two distinct peaks during the experiment. The first and highest peak occurred during the ignition phase, reaching approximately $255,166$ particles/cm³. The second peak corresponds to the particle leakage and distribution measurements conducted around the stove and chimney system. During this phase, the highest particle concentrations were recorded along the horizontal section of the chimney, particularly near the chimney joints, where values reached approximately $249,513$ particles/cm³. In comparison, the vertical chimney section and the areas surrounding the stove body exhibited considerably lower particle concentrations.

The measurements also revealed a vertical stratification of particles within the room. At lower heights, particle concentrations were relatively low and generally increased with height, indicating an accumulation of particles in the upper part of the room. At the interface where the chimney was inserted through the wooden board, visible gaps were present. However, particle concentrations measured at this location were lower than those observed along the horizontal chimney section. This indicates that airflow through the opening was influenced by backdraft, allowing comparatively

cleaner outdoor air to enter the room. Overall, the results suggest that the horizontal chimney section and its joints represent critical locations for particle leakage.

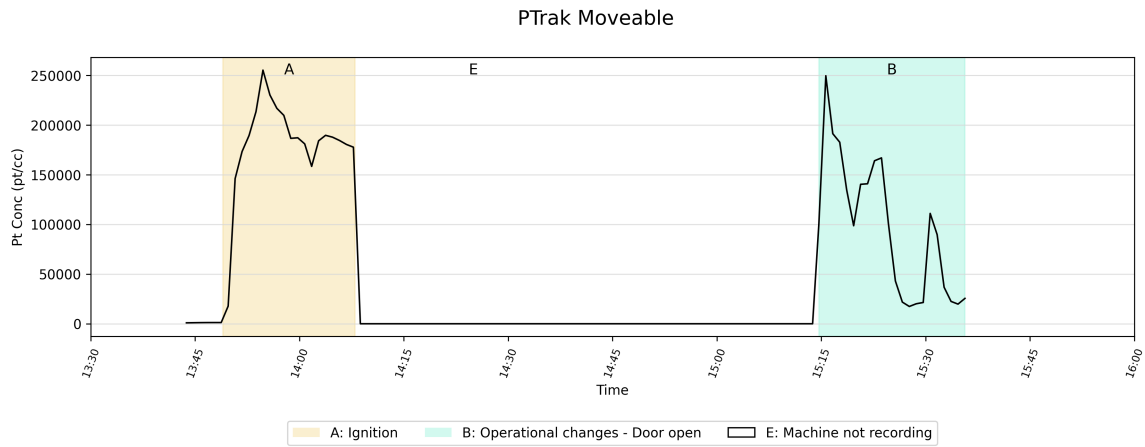


Figure 6.2: P-Trak Movable Reading for the March 4th.

Table 6.1: Particle concentration around the stove and chimney at ignition for Day 1

P-Trak - Movable Locations	Particle Concentration (pt/cm ³)
Horizontal section of the chimney	Maximum around 250,000
Interface between the chimney and the wooden board	30,000–40,000
Floor level and around the stove	59,000–60,000
Angled section of the chimney	100,000–150,000
Combustion chamber of the stove	95,000–98,000
Vertical section of the chimney	80,000–90,000

6.1.4 Smoke puffer test

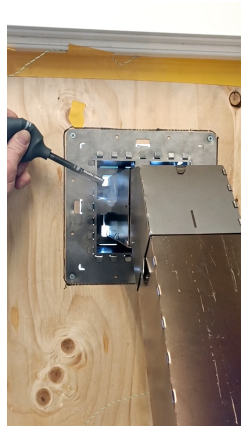


Figure 6.3: Smoke puffer used on the chimney

When smoke was introduced using a smoke puffer near the joints of the horizontal chimney, as shown in figure 6.3, it was observed to rise upward, indicating the influence of buoyancy due to hot air. In contrast, at the interface between the chimney and the wooden board, smoke tended to flow back into the room, indicating the presence of backdraft where outside cleaner air enters the room via this gap.

At this stage, the room was under moderate negative pressure (approximately -6.3 Pa). This condition substantially influenced the observed airflow behaviour. The imposed underpressure increased the tendency for air to be drawn into the room through available openings, including joints and gaps in the chimney system. This behaviour is consistent with the elevated particle concentrations measured at these locations, indicating leakage and disturbed flow patterns under moderate underpressure conditions.

6.1.5 System Response to Operational Changes

- **Opening door:** Upon opening the door, the room pressure shifted towards neutral conditions, and a noticeable reduction in pollutant levels was observed. This indicates that increasing the availability of fresh air improves ventilation effectiveness and reduces the accumulation of combustion products within the room. When the door was closed again, particle concentrations increased rapidly, particularly along the chimney sections. This demonstrates that the system is highly sensitive to pressure changes and that restricted air supply contributes to pollutant buildup.
- **Fuel addition:** Immediately after adding the logs, visible smoke leakage was observed from the stove hatch and along sections of the chimney. This suggests that the combustion process was not stable under the prevailing conditions, likely due to insufficient air supply. To address this, the door and window were opened to enhance airflow, allowing the fire to stabilize and reducing visible emissions. This step highlights the importance of adequate air supply for proper combustion.
- **Extract fan OFF:** Following this change, a reduction in particle concentrations and visible leakage was observed, along with a shift towards a less negative pressure condition within the room. This indicates that the fan-induced airflow had a significant influence on the system behaviour, particularly in promoting leakage and unfavourable airflow patterns under stronger underpressure conditions .
- **Damper:** After the extract fan was switched ON, partially closing the damper resulted in a reduction in airflow and a change in room pressure, leading to more stable conditions. Fully closing the damper further reduced leakage along the chimney.
- **Window:** Opening the window introduced an additional air inlet, which

helped stabilize the pressure conditions and reduce particle concentrations near the chimney. When the window was closed again, particle concentrations increased, indicating that limiting air supply leads to poorer ventilation performance and increased pollutant accumulation. This step confirms that the availability of fresh air plays a critical role in maintaining stable combustion and airflow.

Throughout these interventions, it was observed that the system behaviour is strongly dependent on the balance between air supply and extraction. Conditions with high underpressure and limited air supply resulted in unstable combustion, leakage, and elevated particle concentrations. In contrast, increasing air availability through openings or reducing mechanical extraction improved system performance.

The results demonstrates that the stove does not perform effectively under substantially moderate underpressure conditions and that proper control of airflow and pressure is essential for stable combustion and reduced emissions.

6.1.6 P-Trak static

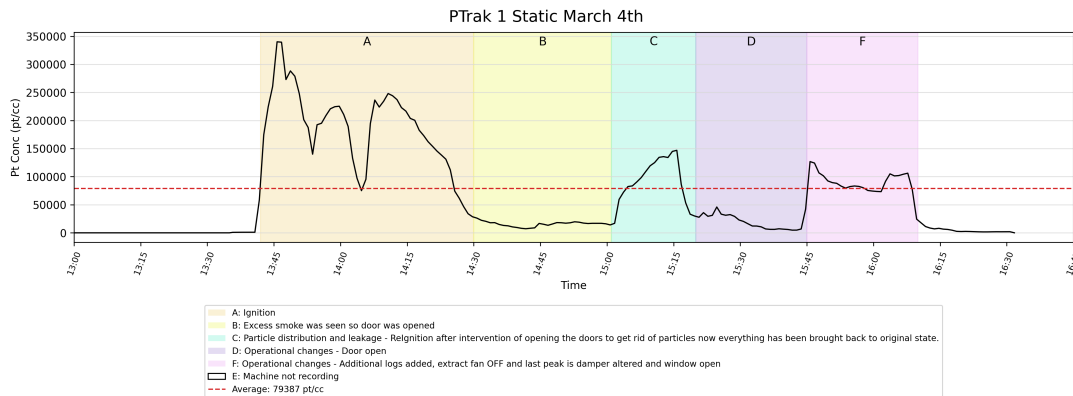


Figure 6.4: P-Trak Static Reading for the March 4th.

The P-Trak measurements exhibited distinct peaks corresponding to different operational activities, as illustrated in the graph figure 6.4. It is important to note that ultrafine particles (UFP) are quantified based on particle number concentration rather than mass concentration, unlike particulate matter (PM). This is because UFPs have extremely low mass but occur in very high numbers. Ultrafine particles (UFP) currently do not have established guideline values however, many studies refer to indicative ranges based on WHO related references to provide a basis for interpretation. According to the World Health Organization (WHO) [15], a peak number concentration exceeding 20,000 particles/cm³ (1-hour mean) is considered high. In the present study, the average UFP concentration from the start of ignition until the end of the measurement period was approximately 79,387 particles/cm³. In addition, the maximum recorded concentration reached approximately 350,000 particles/cm³ during the ignition phase. Both the average and peak concentrations

were substantially higher than the indicative reference level, suggesting elevated ultrafine particle exposure during stove operation, particularly during ignition and periods of unstable combustion.

6.1.7 Dusttrak

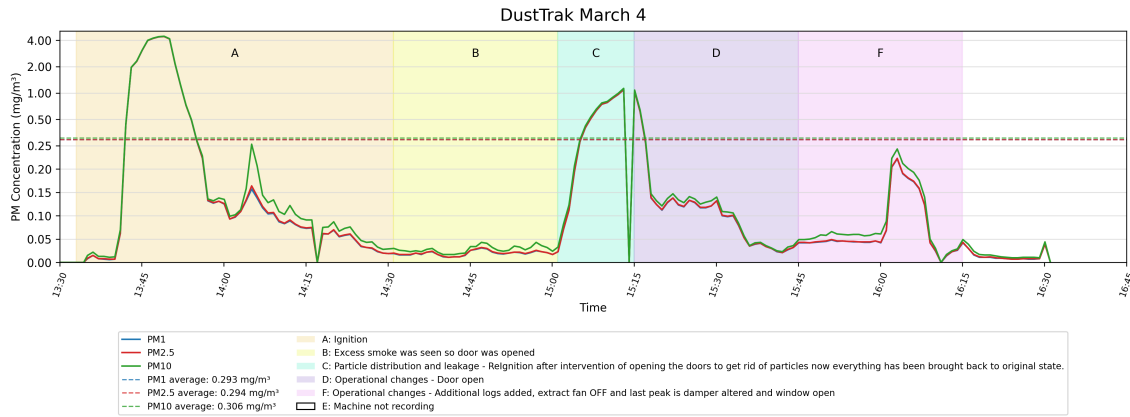


Figure 6.5: Dusttrak Reading for the March 4th.

PM₁, PM_{2.5}, and PM₁₀ refer to particulate matter with aerodynamic diameters smaller than 1 μm , 2.5 μm , and 10 μm , respectively. The particulate matter (PM₁, PM_{2.5}, and PM₁₀) concentrations were observed to be within a similar range follow a trendline throughout the experiment, as shown in the figure 6.5. This indicates that a large proportion of the particles generated were in the ultrafine particle (UFP) size range which are particles smaller than 0.1 μm . Furthermore, they fall within all PM size fractions (PM₁, PM_{2.5}, and PM₁₀), and are therefore detected across all these measurement categories. These ultrafine particles are predominantly generated during wood combustion, particularly during phases of ignition and unstable burning. Additionally, the temporal variation of PM concentrations shows that peaks and reductions correspond closely with stove operation events, such as ignition, opening, and closing of the stove. This confirms that combustion activity is the primary source of particulate emissions in the system.

The maximum recorded values were slightly above 4 mg/m^3 which is 4000 $\mu\text{g}/\text{m}^3$ for all PM fractions, which is significantly higher than the threshold values specified by the World Health Organization (WHO) for indoor air quality refer table 6.2.

In addition to the peak concentrations, the average concentrations from the start of ignition until the end of the experiment were calculated as 0.294 mg/m^3 (294 $\mu\text{g}/\text{m}^3$) for PM₁, 0.294 mg/m^3 (294 $\mu\text{g}/\text{m}^3$) for PM_{2.5}, and 0.306 mg/m^3 (306 $\mu\text{g}/\text{m}^3$) for PM₁₀. Although no specific WHO guideline currently exists for PM₁, the PM_{2.5} guideline value is often used as a reference. When compared with the WHO 24-hour mean guideline values of 15 $\mu\text{g}/\text{m}^3$ for PM_{2.5} and 45 $\mu\text{g}/\text{m}^3$ for PM₁₀, the measured average concentrations were substantially higher. Since the WHO guideline values

are based on 24-hour averages and the present measurements cover only approximately four hours, the comparison should be regarded as indicative.

It should also be noted that few temporary drops in concentration, approaching zero, can be observed throughout the measurement period. These dips are attributed to the instrument's internal measurement cycle and automatic range adjustment process rather than actual reductions in particle concentrations within the room.

In Sweden, WHO guidelines [16] are typically referenced for indoor environments, while outdoor air quality is regulated by standards such as the Miljökvalitetsnormer (MKN) and the Frisk Luft environmental quality objectives.

The exceedance of guideline values indicates that the combustion conditions during the experiment resulted in elevated particulate exposure.

Table 6.2: WHO guideline for PM_{2.5} and PM₁₀

Pollutant	Time period	WHO guideline ($\mu\text{g}/\text{m}^3$)
PM _{2.5}	Annual mean	5
PM _{2.5}	24 hour mean	15
PM ₁₀	Annual mean	15
PM ₁₀	24 hour mean	45
PM ₁	Annual mean	Refer to PM _{2.5} values since no guidelines yet
PM ₁	24 hour mean	Refer to PM _{2.5} values since no guidelines yet

It is to be noted that the DustTrak aerosol monitor is factory calibrated using Arizona road dust, which differs in physical and optical properties from wood smoke aerosols generated during combustion. Consequently, the reported particulate matter concentrations should be interpreted as indicative values, as optical aerosol monitors may overestimate particulate mass concentrations from combustion sources. However, both the peak and average PM concentrations measured during the experiment exceeded the relevant guideline values by a substantial margin. Therefore, even if some degree of overestimation is present, the overall conclusion regarding elevated particulate exposure during stove operation remains unchanged. The instrument is therefore considered suitable for assessing particulate emission trends and relative changes during the experiments.

6.1.8 RESP

RESP can be defined as the respirable fraction of particulate matter, representing the mass concentration of particles small enough to penetrate deep into the human respiratory system and potentially cause adverse health effects. These particles are typically associated with PM₄ size fractions. In this study, the average RESP concentration over the entire Day 1 experimental period was approximately 0.262 mg/m³ refer figure 6.6. Respirable particles are commonly associated with industrial environments, and therefore, the corresponding exposure guidelines are gen-

erally established by occupational and industrial health organizations rather than environmental agencies.

A comparison with the relevant guideline values, as presented in the table 6.3, indicates that the measured RESP concentration remains well within acceptable limits. Both $PM_{2.5}$ and RESP indicate particles that can enter the respiratory system, but $PM_{2.5}$ represents a more conservative measure of fine particle exposure. It should be noted that the reference values presented in table 6.3 are based on occupational exposure standards intended for industrial workplace environments. Consequently, they are not directly comparable to residential indoor air quality guidelines and are included here primarily to provide context for the measured RESP concentrations.

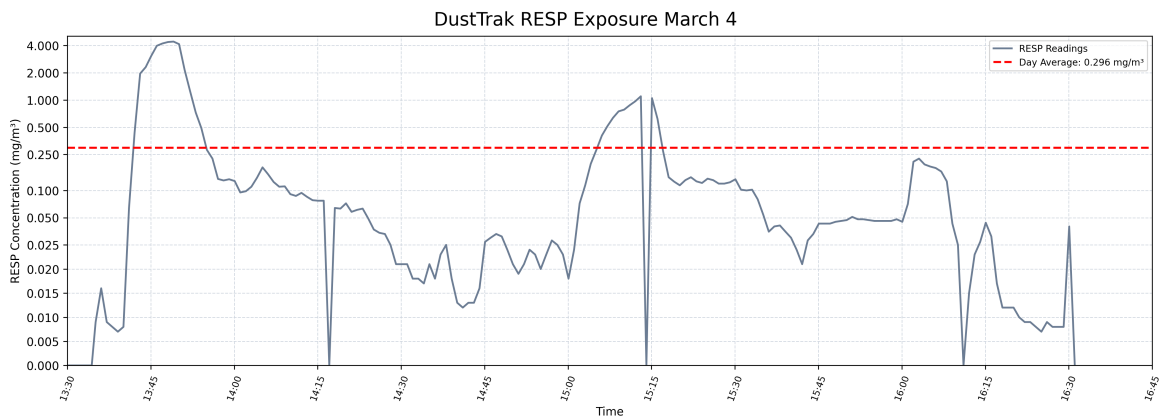


Figure 6.6: RESP curve for DAY 1

Table 6.3: Respirable PM_4 exposure limits by organisation and country

Oragnisation	Country	Resp PM_4 value (mg/m^3)
OSHA [17]	USA	5
Arbetsmiljöverket [18]	Sweden	2.5–5
AGV [19]	Germany	1.25

6.1.9 Multigas monitor CO , CO_2 , TOC and T_{dew} Values

The temporal variation of gaseous pollutants (CO , CO_2 , and TOC) indicates that all parameters follow a similar trend, closely linked to stove operation phases such as ignition, fuel loading, and stabilization.

Carbon monoxide (CO) concentrations reached a maximum value of approximately 15 ppm during ignition and refuelling, particularly following interventions such as opening the stove door, as shown in figure 6.8. In comparison, the average CO concentration from the start of ignition until the end of the experiment was approximately 1.96 ppm. When compared with the WHO guideline value of 9 ppm (8-hour mean) refer table 6.4, the peak concentration exceeded the recommended

limit, whereas the average concentration remained below it. The WHO guideline is based on an 8-hour average, whereas the present measurements covered approximately four hours therefore, the comparison is indicative only.

Nevertheless, the observed peak concentration is also important, as short term increases in CO may indicate periods of incomplete combustion and shows periods with excessive generation of pollutants from the stove. Carbon monoxide is a colourless and odourless toxic gas that can reduce the oxygen carrying capacity of the blood, and elevated concentrations is fatal and may lead to symptoms such as headache, dizziness, fatigue, and impaired cognitive performance. Therefore, both average and peak CO concentrations are relevant when evaluating the safety of indoor wood stove operation.

Carbon dioxide (CO₂) concentrations showed a steady increase refer figure 6.8, during combustion and a clear decay phase during the tracer gas experiment. The highest CO₂ concentration observed during stove operation was approximately 1720 ppm, while a higher value of approximately 2300 ppm was recorded during the CO₂ decay test prior to ignition. Since the latter was associated with the tracer gas experiment rather than combustion, it is not considered representative of stove performance and was therefore excluded from the combustion related analysis. The average CO₂ concentration during the experimental period after ignition was approximately 842 ppm. When compared with the commonly referenced indoor air quality threshold of 1000 ppm, the peak concentration during combustion exceeded the recommended level, whereas the average concentration remained below it. Elevated CO₂ concentrations may indicate limited ventilation and the accumulation of combustion products within the room.

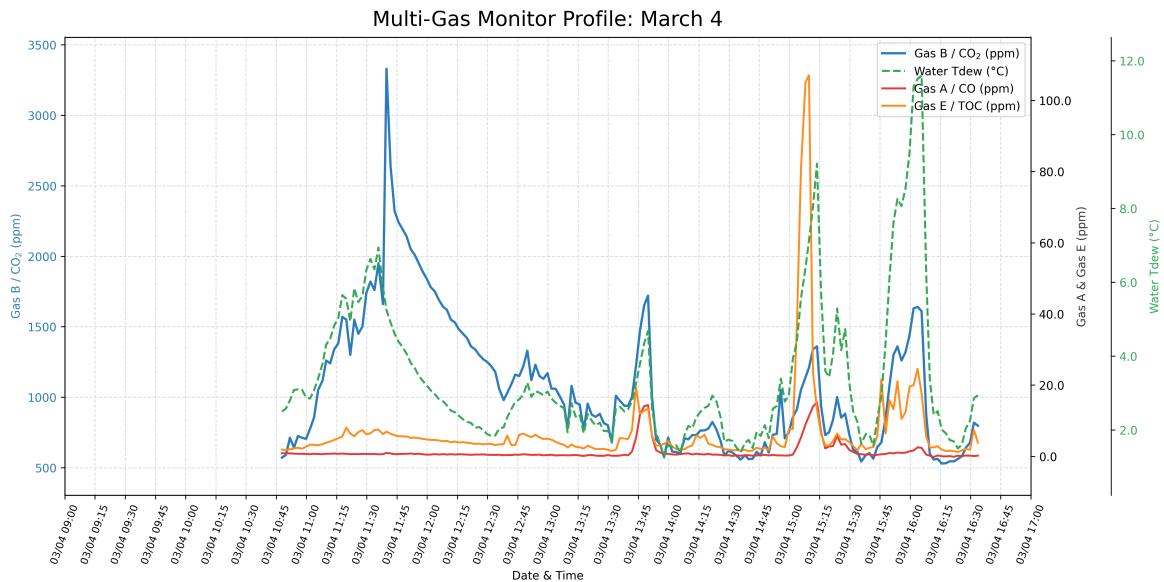


Figure 6.7: Mutligas monitor gas readings March 4th

Although CO₂ is not typically considered toxic at the concentrations observed in this study, elevated levels may indicate insufficient ventilation and the accumulation

6. Experimental Results and Analysis

of combustion products indoors.

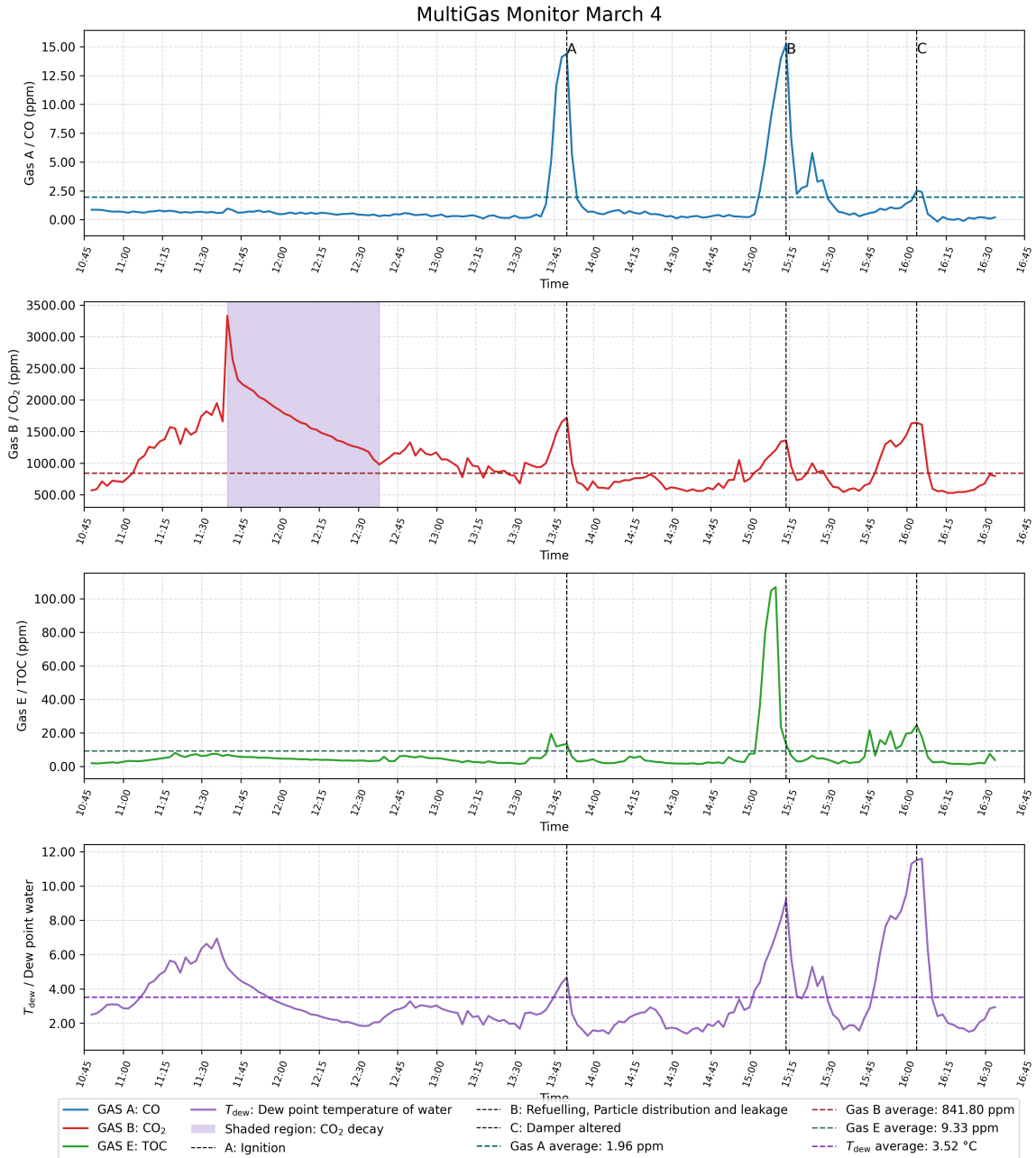


Figure 6.8: Multigas monitor results for March 4

Similarly, total organic compound (TOC) concentrations increased during the refuelling phase, reaching a peak value of approximately 105 ppm, while the average concentration over the experimental period after ignition was approximately 9.33 ppm. Although no widely accepted indoor air quality guideline exists for TOC, the elevated concentrations observed during ignition and refuelling indicate the release of unburned hydrocarbons and periods of degraded indoor air quality associated with combustion disturbances.

T_{dew} and CO_2 exhibited similar trends throughout the experiment. This behaviour may be attributed to several factors. The major contributing factor may be that wood combustion generates water vapour alongside CO_2 , leading to concurrent increases in indoor moisture content and CO_2 concentrations. Furthermore, the instrument response during CO_2 injection may also contribute to the observed similarity in trends, as the sensor may not fully differentiate between rapid environmental changes associated with gas injection, humidity, and combustion related effects.

Overall, the results demonstrate that pollutant emissions are strongly influenced by combustion stability and ventilation conditions, with ignition and fuel loading representing critical phases associated with elevated indoor air pollution.

Table 6.4: Guideline for CO and CO_2

Quantity	Guideline	Limits
CO	WHO	9 ppm (8-hour mean)
CO_2	Boverket	< 1000 ppm (good ventilation), 1000–1500 ppm (acceptable)

6.1.10 Thermocouple

The thermocouple measurements indicate a clear spatial variation in temperature within the room during stove operation. Since the graph represents the average of all four thermocouple nodes, it illustrates the overall temperature trend at each measurement location rather than the variation at individual heights. The thermocouple positioned near the chimney region recorded the highest average temperatures, reaching approximately 33°C , whereas the thermocouple positioned according to ISO 7730 measurement heights recorded a maximum average temperature of approximately 28°C .

The highest temperature measured on the thermocouple pole was 37.3°C (Node 2), while the highest temperature on the window board was 40.8°C (Node 2). The maximum temperatures recorded at the bottom and top of the pole were 26.4°C (Node 1) and 32.2°C (Node 4), respectively.

The results also demonstrate the heating capability of the stove, as the room temperature increased from approximately 14°C prior to ignition to around 23°C within the occupied zone during operation, indicating that the stove was capable of effectively heating the space. However, the occupied zone temperature exceeds the typical indoor thermal comfort range recommended in Swedish building guidance (approximately $20\text{--}24^\circ\text{C}$), suggesting localized overheating and heat accumulation within the relatively small and airtight room.

The elevated temperatures near the chimney are attributed to direct heat transfer and the upward movement of hot combustion gases. This difference indicates the presence of localized heating near the chimney and demonstrates that heat dis-

tribution within the room was non-uniform. It should be noted that the primary objective of this study was not to perform a detailed indoor thermal comfort or room temperature assessment, but rather to investigate pollutant behaviour and stove performance under different operating conditions. Furthermore, the experimental setup was conducted in a relatively small room, which may have contributed to the observed temperature increase.

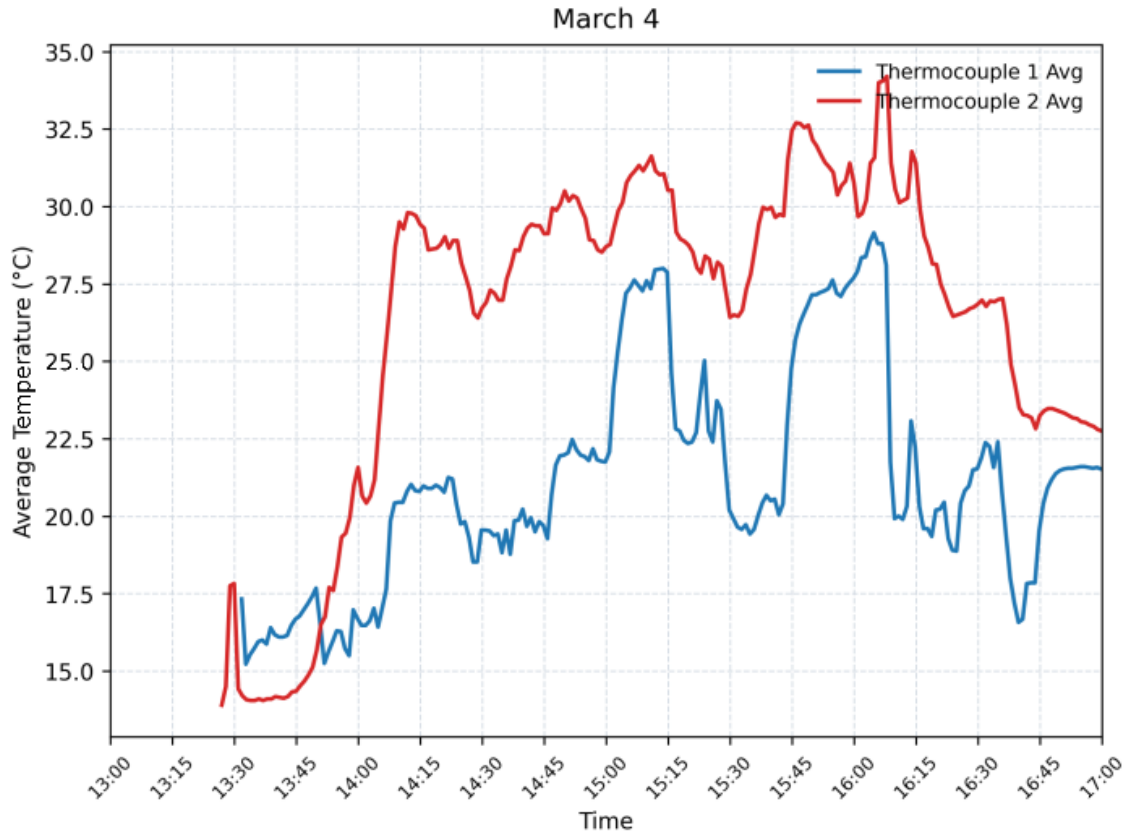


Figure 6.9: Thermocouple average March 4th, Thermocouple 1 – Pole, Thermocouple 2 – Placed on the window wooden board near the chimney

Previous studies conducted by the RISE Research Institutes of Sweden have reported a nominal heating capacity of 4 KW for the FirePipe stove. Therefore, the temperature results should be interpreted primarily as an indication of the stove’s heating effect within the specific experimental environment rather than as a comprehensive assessment of thermal comfort or heating performance in a typical residential setting.

6.1.11 Key Findings for Day 1 (March 4th)

Based on the experimental observations, it was identified that the system performance was strongly affected by limited air supply under negative pressure conditions. Under these conditions, significant backdraft and leakage were observed along the chimney joints and stove openings, accompanied by elevated particle concentrations.

During the experiment, it was observed that introducing additional air into the room, such as by opening the door or window, resulted in improved combustion behaviour and a reduction in pollutant levels.

Air movement within the room is primarily driven by the combined effect of air extraction and combustion processes. The operation of the extract fan, along with the upward draft in the chimney, results in the removal of air from the room, thereby creating a negative pressure condition. In addition, the combustion process within the stove requires a continuous supply of oxygen.

As a result, air is drawn into the room through available openings and leakage paths in order to compensate for the extracted air and sustain combustion. In the absence of a dedicated air inlet, this incoming airflow occurs through unintended locations such as chimney joints, gaps, and stove openings, leading to unfavorable airflow patterns and leakage.

These observations suggest that the absence of a controlled air inlet leads to unfavorable airflow patterns. A potential solution identified from the observations is the introduction of an opening in the wooden board near the chimney. Such an opening would provide a direct and consistent air supply and a defined location for air exchange, which may reduce the reliance on unintended leakage paths such as chimney joints and gaps.

By introducing a designated opening, airflow into the system may become more predictable compared to the existing condition, where air movement occurs through multiple uncontrolled paths. This could contribute to improved combustion conditions and reduced leakage. However, further investigation would be required to confirm the effectiveness of this approach.

6.2 Experimental Result and Analysis - March 5th

6.2.1 Hole /opening test

Following the creation of the opening in the window board, the room pressure changed depending on door conditions. When both the room and building doors were open, the room exhibited a slight over pressure (approximately +1 Pa). When the door was closed, the pressure shifted towards negative values, stabilizing near 0 Pa before decreasing further.

The relationship between opening size and room differential pressure refer table 6.5, was evaluated at airflow rates of 11 L/s, 20 L/s, and 30 L/s . At larger opening sizes, the differential pressure was close to 0 Pa, suggesting effective pressure equalization, airflow and good mixing between indoor and outdoor air. As the opening size was gradually reduced, the under pressure inside the room increased(-2.8 Pa at 11 L/s, -6.9 Pa at 20 L/s and -11.7 Pa at 30 L/s). This increase was non-linear, with the differential pressure approximately doubling at smaller openings, particu-

larly at 4 cm and when fully closed which can be seen in figure 6.11. Furthermore, consistent trends were observed across all tested airflow rates (11 L/s, 20 L/s, and 30 L/s), reinforcing the reliability of the results.

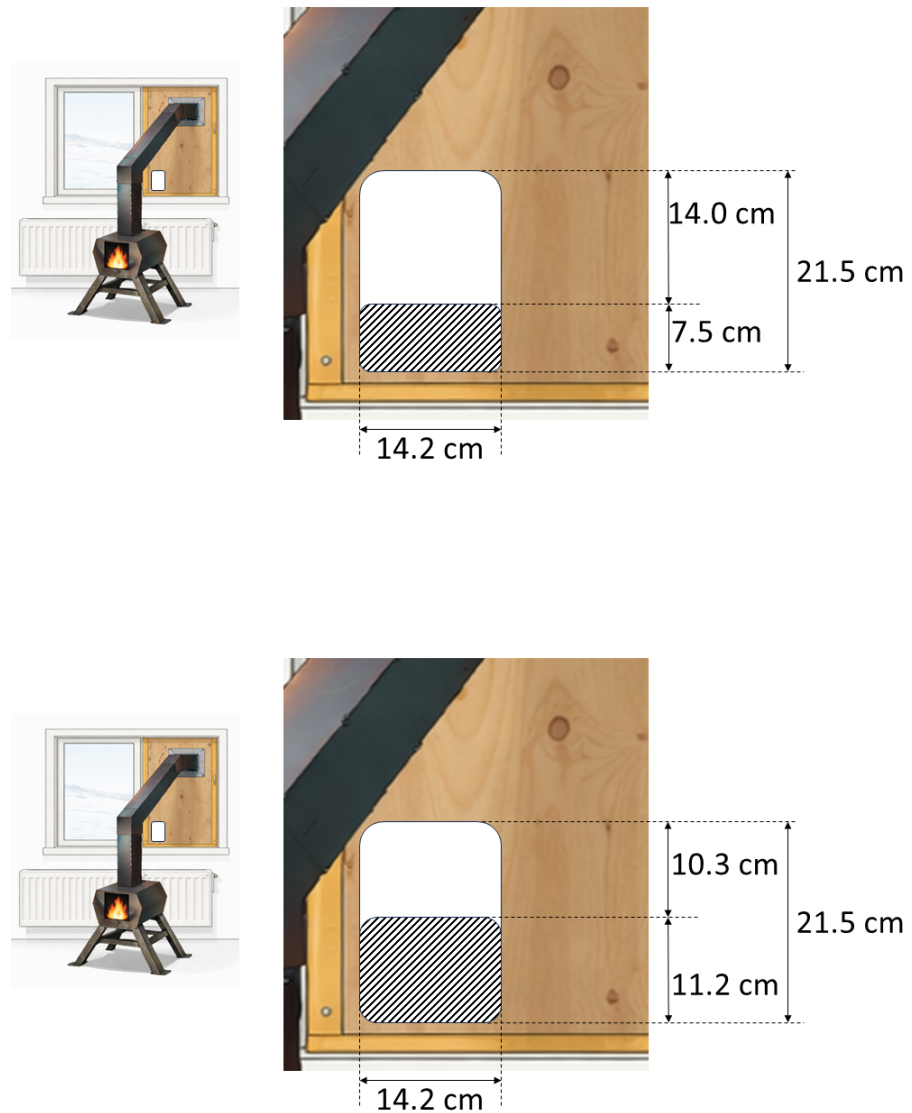
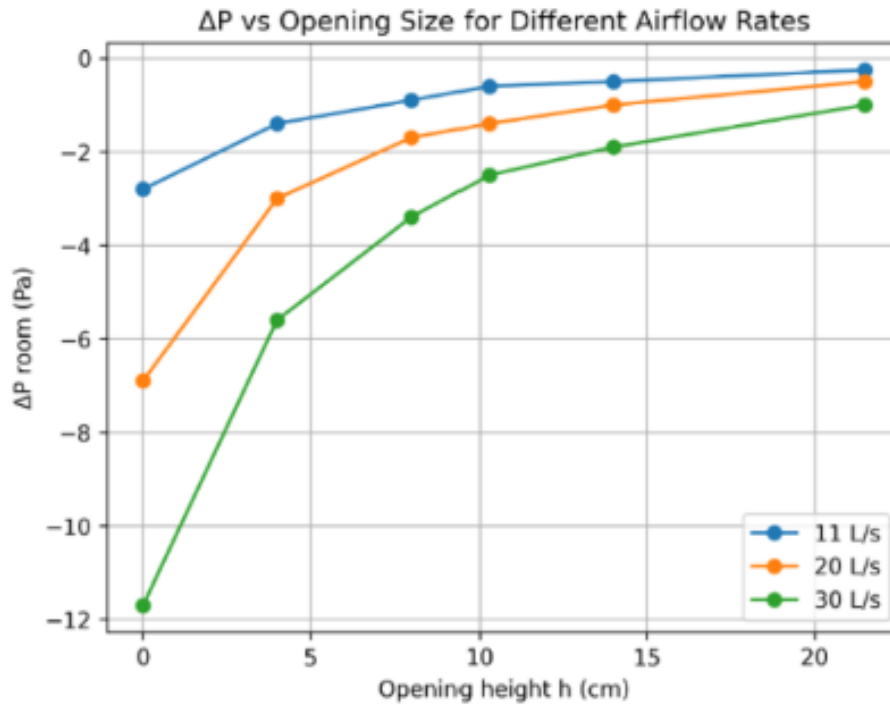


Figure 6.10: Illustration of the opening in the window wooden board below the chimney, showing partially covered configurations. The shaded region represents the covered portion of the opening (7.5 cm), while the remaining section (14 cm) represents the effective opening area. A similar configuration is shown for the 10.3 cm opening, with a corresponding shaded (covered) region(11.2 cm).

Table 6.5: Effect of Opening Size on Room Differential Pressure at Airflow Rates of 11 L/s, 20 L/s, and 30 L/s

Opening Height, h (cm)	ΔP at 11 L/s (Pa)	ΔP at 20 L/s (Pa)	ΔP at 30 L/s (Pa)
Fully open – 21.5	–0.2 to –0.3	–0.5	–1.0
14	–0.5	–1.0	–1.9
10.3	–0.6	–1.4	–2.5
8	–0.9	–1.7	–3.4
4	–1.4	–3.0	–5.6
Fully covered – 0	–2.8	–6.9	–11.7

Although the opening was not initially optimized, these findings demonstrated that the opening size is appropriate acts as a pressure relief pathway, as it ensures adequate air exchange and balance the extraction. Increasing the opening is not necessary, while reducing it leads to undesirable under pressure conditions.

**Figure 6.11:** Graph of Opening Size vs ΔP

6.2.2 Flap Assessment/flap test:

For the purpose of achieving some degree of automatic regulation of the air supply through the opening in the wooden board, various designs of a flap were explored. A total of four flap prototypes were tested at the extract airflow rate of 20 L/s and with the stove switched OFF, see table 6.6.

Table 6.6: All the prototypes and its influence on differential pressure of the room

Prototype	Air Flow Rate, v (L/s)	ΔP Room (Pa)	Position/Behaviour of Flap
Plastic sheet prototype – P1	20	–1.3	No interference. Arbitrary movement observed.
Plastic sheet prototype – P2	20	–1.4	No interference. Arbitrary movement observed.
Laminated photopaper prototype – P3	20	–0.8	Stable flap behaviour observed. No interference. Arbitrary movement observed.
Plastic sheet prototype – P4 (same material as P1 but half its thickness)	20	–1.0	Improved flexibility due to reduced thickness. No interference. Arbitrary movement observed.

6.2.2.1 Prototype Selection

At an airflow rate of 20 L/s, Prototype 3 (P3) yielded a differential pressure of -0.8 Pa, which was better than the other prototypes. Based on this observation, P3 was selected for further testing.

Prototype 3 was subsequently tested at 10 L/s, 20 L/s, and 30 L/s, and consistent performance was observed across all airflow conditions.

Table 6.7: Prototype P3 and its influence on the differential pressure of the room

Plastic sheet prototype – P3 – second test		
v (L/s)	ΔP room (Pa)	Position of flap
30	–1.4	No interference. Arbitrary movement observed.
20	–0.9	
10	–0.5	

Prototype 3 (P3), consisting of laminated photo paper, was selected as the most suitable of the tested flap materials. This selection was primarily based on its performance at an airflow rate of 20 L/s, where it produced the least negative pressure compared to the other prototypes.

In addition to this, P3 was the only prototype that resulted in a pressure difference close to 0 Pa, indicating the absence of excessive suction while still allowing

controlled airflow between the indoor and outdoor environments. This balance is critical for maintaining stable pressure conditions within the room. Maintaining differential pressure close to neutral is important, as previous results showed that even moderate under pressure leads to unfavorable airflow and increased pollutant leakage.

From a material perspective, P3 exhibited an optimal balance between rigidity and flexibility. Unlike thicker plastic materials, it was not excessively rigid, and unlike thinner plastic sheets (as in Prototypes 1, 2, and 4), it was not overly flexible. This allowed the flap to open and close smoothly in response to pressure variations without exhibiting erratic motion.

Furthermore, the plastic based prototypes (P1, P2, and P4) were observed to flutter excessively and overreact to external wind conditions, leading to unstable behaviour. In contrast, P3 was neither too light nor too heavy, demonstrated a natural damping effect, resulting in reduced fluctuations and more stable system performance. It did not resist movement under relevant pressure differences.

It is to be noted that P3 is not weather resistant or water resistant. However, this study focused on evaluating performance, and among the tested prototypes, P3 showed the best results. Other materials are currently being tested by the FirePipe company for real world use.

Finally, when tested across multiple airflow rates, P3 exhibited consistent performance, further supporting its suitability. Based on these observations, Prototype 3 was identified as the most effective solution for this application.

The selected flap (P3), when combined with the opening, allows sufficient air intake while preventing excessive under pressure. This confirms that the flap opening system functions effectively as a pressure regulation mechanism.

6.2.3 Ignition

A set of tests were conducted with the stove during combustion with the flap (P3) installed. During the start of the ignition phase the extract airflow was 11 L/s, the room pressure was approximately -0.8 Pa, and the CO concentration was around 0.5 ppm. The CO₂ decay test was initiated immediately after stove ignition, and the subsequent variation in CO₂ concentration was monitored throughout the measurement period. Further details regarding the CO₂ decay measurements are provided in the appendix.

An increase in ultrafine particle (UFP) concentration was observed during the initial combustion phase. These elevated concentrations were attributed to particle dispersion during ignition and fuel loading, which is discussed below.

Using P-Trak instruments, UFP measurements were taken at three locations: near

6. Experimental Results and Analysis

the chimney junction, around the stove chamber, and at a distance from the unit on the table (P-Trak static). Measurements using the P-Trak instruments showed that UFP concentrations varied by location. The highest concentrations were found at the furthest measurement point on the table (around 230,000 particles/cm³ from figure 6.13), followed by the chimney junction joints, with the area around the stove showing lower relative levels.

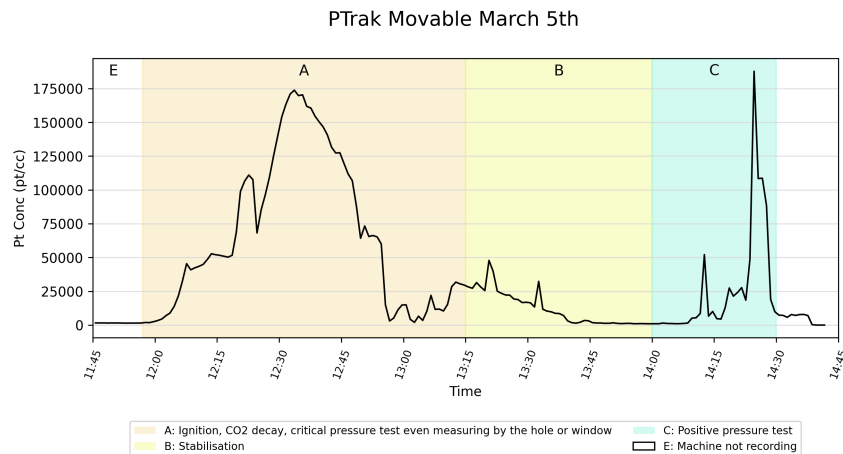


Figure 6.12: P-Trak Movable Reading for the March 5th.

The spike at the chimney junction was attributed to leaks at the duct joints and the upward movement of combustion particles. In contrast, the high levels recorded at the table were likely due to the equal mixing of gases and particle dispersion throughout the room during ignition and fuel loading. The area immediately surrounding the stove remained relatively stable, suggesting minimal leakage from the main combustion chamber. These elevations occurred primarily during ignition and refuelling

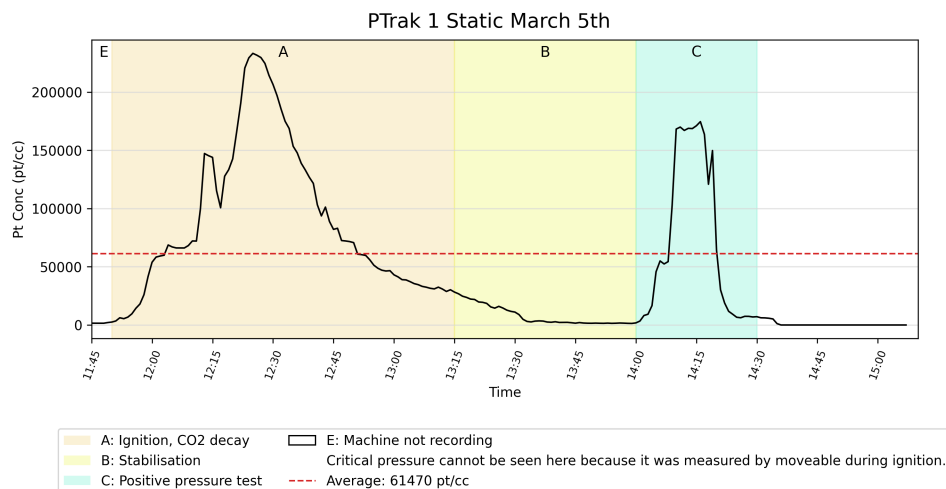


Figure 6.13: P-Trak Static Reading for the March 5th.

6.2.4 Critical Pressure Test

Table 6.8: Variation of particle concentration with room differential pressure

ΔP room (Pa)	P-Trak Movable (particles/cm ³)	Air flow rate (L/s)	Note
−2.0	29 000	30	
−2.5	29 000	30	Partly covered hole
−3.8	26 000	30	Progressively, the hole was closed using a board
−4.7	10 000	30	
−5.8	$\sim 2 \times 10^5$	30	Critical pressure
−6.3	$\sim 2 \times 10^5$	30	

The results of the critical pressure condition test are presented in table 6.8, showing the variation of ultrafine particle (UFP) concentration with room pressure under a constant high airflow rate of approximately 30 L/s. The particle concentrations reported in table 6.8 were manually recorded from the movable P-Trak at specific pressure conditions and therefore represent localized spot measurements. The P-Trak responds rapidly to changes in local particle concentration. However, the logged data were recorded at one minute intervals and do not capture every fluctuation occurring between successive logging points. Since the instrument was continuously moved between measurement locations during the experiment, short term variations observed on the display and recorded manually may not be fully reflected in the continuous time series data shown in figure 6.12. Therefore, some differences between the manually recorded values and the logged measurements may occur due to the instrument's response to rapidly changing local particle concentrations and the selected logging interval.

At lower levels of under pressure (from −2.0 Pa to −3.8 Pa), the particle concentration remains relatively stable, ranging between 29,000 and 26,000 particles/cm³, indicating controlled airflow conditions and stable pollutant levels. As the pressure becomes more negative (around −4.7 Pa), a noticeable reduction in particle concentration is observed ($\sim 10,000$ particles/cm³). The cause of the temporary reduction in particle concentration at −4.7 Pa cannot be determined with certainty from the available measurements and may have been influenced by local airflow conditions, measurement location, short term concentration fluctuations, or external factors such as wind conditions.

After the measurements at −4.7 Pa, noticeable changes in system behaviour were observed at approximately −6.3 Pa. To further investigate the system behaviour within this intermediate range, the airflow rate and the extent of opening coverage were adjusted incrementally to vary the room differential pressure between −4.7 Pa

and -6.3 Pa. This was achieved by progressively covering the hole with a board, allowing finer control over the pressure conditions. Through this approach, an intermediate pressure level of approximately -5.8 Pa was obtained.

Beyond this point, a drastic change in system behaviour was observed. At pressures around -5.8 Pa and lower, the ultrafine particle concentration increased sharply to approximately $200,000$ particles/cm³. This increase is also reflected in the movable P-Trak measurements shown in figure 6.12 with a value of $173,766$ particles/cm³, indicating a sudden deterioration in indoor air quality. This identifies -5.8 Pa as the critical pressure threshold, beyond which the airflow becomes unfavorable and leads to increased pollutant levels.

The main outcome of this test was the identification of a critical pressure threshold, beyond which the system no longer operates in a stable or safe manner. Based on these observations, approximately -5.8 Pa was identified as a critical pressure condition for the specific room, stove, chimney, and ventilation configuration used in this study.

6.2.5 Positive Pressure Test

Under positive pressure conditions, an increase in ultrafine particle concentration was observed, particularly near the chimney and extract duct regions of around $187,000$ pt/cc (figure 6.12). The Movable P-Trak recorded higher localized concentrations, while the static P-Trak showed comparatively lower but still elevated value of $174,000$ pt/cc (figure 6.13). The room experienced a positive differential pressure of approximately $+10.3$ to $+10.6$ Pa, indicating a significant deviation from earlier operating conditions.

The observed increase in particle concentration suggests that positive pressure conditions reduce the effectiveness of pollutant removal. The reversal of airflow direction limits the ability of the system to extract pollutants, resulting in their accumulation within the room.

In addition, the disturbance of airflow patterns leads to increased mixing and redistribution of particles, rather than controlled removal. The higher localized concentrations near the chimney and duct further indicate that airflow becomes spatially uneven, with certain regions experiencing higher pollutant levels.

6.2.6 P-Trak

At around 12:00 p.m., particle concentration of P-Trak static increased following stove ignition indicating the release of ultrafine particles during the initial combustion phase (figure 6.13). The concentration peaked at around 12:24 p.m. ($\sim 230,000$ particles/cm³) which is the same time around which critical pressure test was measured by the P-Trak movable device. Following this peak, the concentration gradually decreased, indicating stabilization of combustion and effective ventilation within the room. A second increase in particle concentration was observed at around

14:00 p.m. during the positive pressure test which is already detailed in the earlier section.

Measurements from the P- Trak Movable near the window opening around 12:54–12:56 p.m. showed strong fluctuations, with concentrations reaching approximately 70,000 particles/cm³ before rapidly decreasing (figure 6.12). This suggests that airflow near the opening was strongly influenced by external wind conditions and possible interaction between the nearby chimney and extract outlet.

6.2.7 Dust trak

The similar trends observed for PM₁, PM_{2.5}, and PM₁₀ suggest that most particles generated during the experiment were within the fine particle range, which is consistent with combustion related emissions.

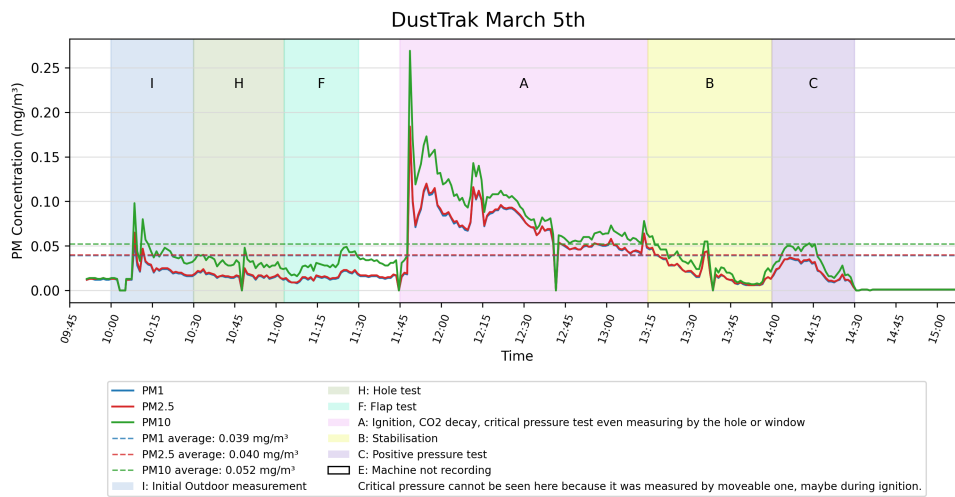


Figure 6.14: Dusttrak Reading for the March 5th.

The maximum recorded PM concentration was 0.27 mg/m³, which exceeds the WHO 24-hour guideline values for PM_{2.5} and PM₁₀. However, these values represent short term peaks associated with combustion related events rather than long term average exposure conditions. During the stabilization phase after ignition, PM concentrations decreased to approximately 0.05 mg/m³ and lower, indicating more stable combustion and improved pollutant removal conditions.

The average particulate matter concentrations measured during the experiment were 0.039 mg/m³ for PM₁, 0.040 mg/m³ for PM_{2.5}, and 0.052 mg/m³ for PM₁₀, corresponding to 39 µg/m³, 40 µg/m³, and 52 µg/m³, respectively. When compared with the World Health Organization (WHO) 24-hour air quality guideline values of 15 µg/m³ for PM_{2.5} and 45 µg/m³ for PM₁₀, the measured average concentrations exceeded both guideline values. However, this comparison should be interpreted with caution, as the experiment was conducted over a measurement period of approximately three hours rather than the 24-hour averaging period used in the WHO guidelines.

PM₁₀ consistently showed higher values than PM_{2.5} and PM₁ due to its broader particle size range, as PM₁₀ includes both fine and larger particles. In addition, combustion related agglomeration, turbulence, and particle resuspension may contribute to elevated PM₁₀ concentrations, particularly during airflow disturbances.

A slight increase in PM concentrations, especially PM₁₀, was observed during the positive pressure test. This behaviour is attributed to disturbed airflow patterns, reduced extraction efficiency, and increased redistribution of particles within the room under positive pressure conditions. In contrast, no major PM deviations were observed during the hole and flap tests, since the stove was switched off and no active combustion related particle source was present.

6.2.8 Multigas Monitor CO, CO₂, TOC and T_{dew} Values

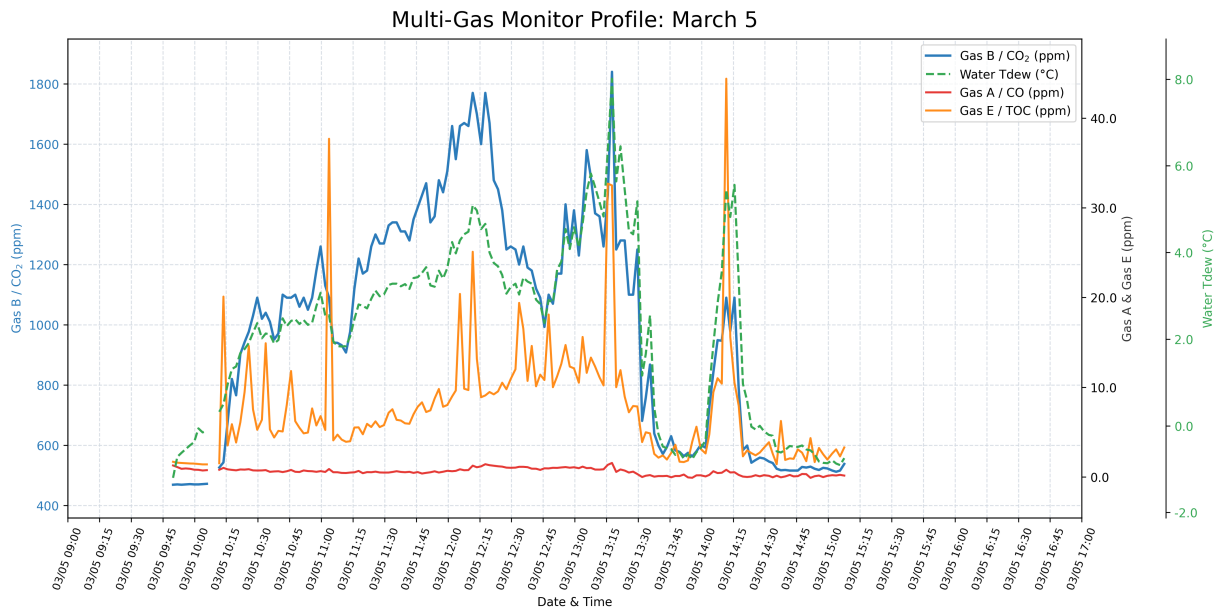


Figure 6.15: Multigas monitor gas readings March 5th

The MultiGas measurements obtained during Day 2 provide an overview of the indoor gaseous pollutant concentrations and moisture conditions during stove operation. CO₂ primarily reflects combustion activity and ventilation conditions, whereas CO is associated with incomplete combustion and limited oxygen supply. TOC represents the release of volatile organic compounds generated during wood combustion. Overall, CO₂, CO, TOC, and dew point temperature followed similar temporal trends throughout the experiment, with increases generally observed during ignition, refuelling, and airflow disturbances.

The average CO₂ concentration from ignition until the end of the experiment was 1008.76 ppm, which is close to the commonly referenced indoor air quality level of 1000 ppm. A peak concentration of approximately 1840 ppm was recorded during

refuelling and particle leakage measurements.

The average CO concentration was 0.54 ppm, with a maximum value of 1.5 ppm observed during refuelling and particle leakage measurements. This average remains well below the commonly referenced WHO 8-hour guideline value of 9 ppm. However, it should be noted that the experiment was conducted over approximately three hours and therefore does not represent a full day or long term exposure period. CO concentrations remained relatively low throughout the experiment when compared to day 1, indicating that incomplete combustion did not affect the room air to a large extent.



Figure 6.16: Mutligas monitor readings March 5th

The average TOC concentration was 8.55 ppm, while a peak value of 44.4 ppm was observed during positive pressure test (damper alterations). This is much lower in concentrations when compared to day 1. Since the TOC sensor reports concentrations as toluene equivalent values, the measurements represent the combined presence of volatile organic compounds released during wood combustion rather than pure toluene alone.

The average dew point temperature was 2.32°C, with a maximum value of 8.01°C recorded during refuelling. Similar to day 1 CO₂ and dew point temperature exhibited similar trends across CO₂ decay phase.

When compared with Day 1, the Day 2 measurements indicate generally lower pollutant concentrations and fewer extreme fluctuations. This suggests that the modifications investigated during the second day contributed to more stable operating conditions and reduced accumulation of combustion related pollutants within the room.

6.2.9 Thermocouple

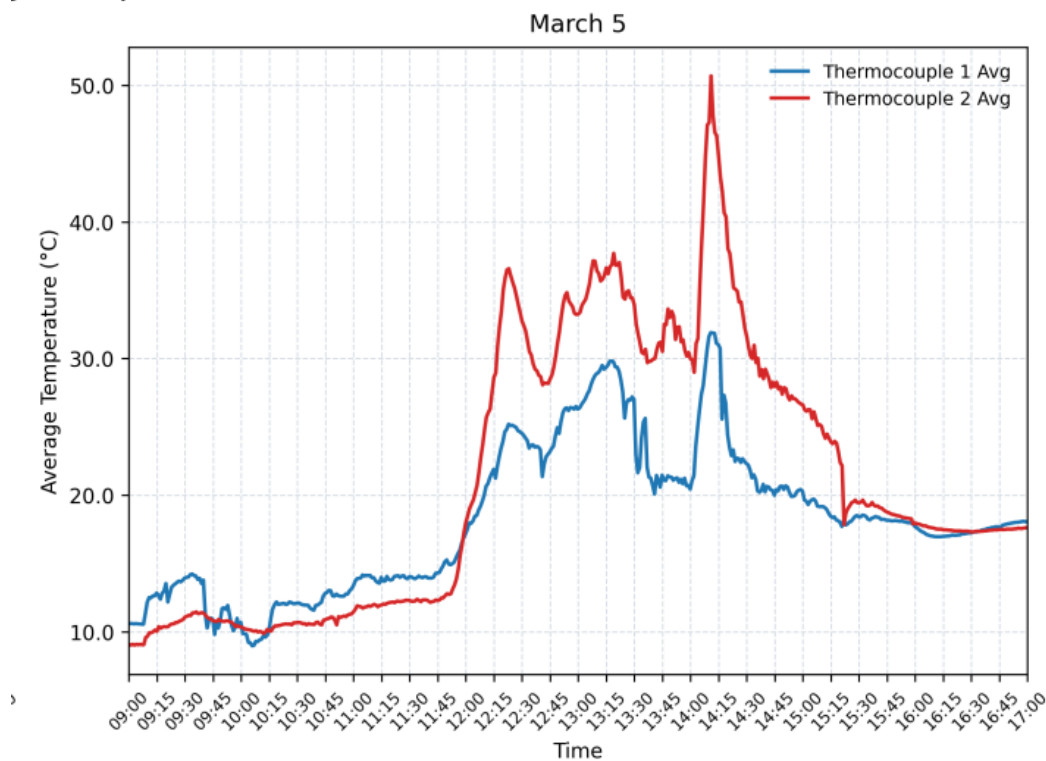


Figure 6.17: Thermocouple Average March 5th Thermocouple 1-Pole
Thermocouple 2- Placed on the window wooden board near the chimney

The thermocouple measurements from March 5 demonstrate the strong heating capability of the stove, with room temperatures increasing from approximately 10°C

prior to ignition to values exceeding 20°C within a relatively short period. Thermocouple 1, representing the occupied zone measurements, generally remained within the range of 20–30°C during stove operation, whereas Thermocouple 2, located near the chimney and window wooden board region, recorded significantly higher temperatures. The highest temperature measured on the thermocouple pole was 43.8°C (Node 2), while the highest temperature on the window board was 72.4°C (Node 2). The maximum temperatures recorded at the bottom and top of the pole were 26.5°C (Node 1) and 36.1°C (Node 4), respectively.

During the positive pressure test at approximately 14:10, a sharp temperature increase was observed near the chimney region, with Thermocouple 2 reaching 50°C. Thermal camera observations conducted during this period identified localized surface temperatures of 62°C near the chimney interface and 46°C on the wooden board surface, while a nearby radiator surface reached 30°C. These observations indicate significant localized heat accumulation and redistribution under positive pressure conditions. Although the occupied zone temperatures generally remained within a potentially habitable range for much of the experiment, temperatures above the recommended Swedish indoor comfort range (approximately 20–24°C) were observed during several periods, indicating temporary overheating conditions within the relatively small and airtight room.

Comparison of the thermocouple measurements from March 4 and March 5 indicates that the room heated more rapidly during the March 5 experiment. On March 4 refer to the figure 6.9, the room temperature increased gradually from approximately 15°C at around 13:30 to approximately 20°C at around 14:10. In contrast, on March 5, the temperature measured by Thermocouple 1, representing the occupied zone breathing height reference, increased from approximately 15°C at around 11:45 to approximately 20°C between 12:00 and 12:15.

This difference suggests that the March 5 configuration provided more effective combustion and heat transfer conditions. The opening/flap system introduced during March 5 likely improved air supply and pressure balance within the room, promoting more stable combustion and increased heat release. In comparison, the more airtight conditions during March 4 may have resulted in more restricted airflow and combustion air availability, contributing to the slower heating response observed during the experiment.

6.2.10 RESP

The RESP measurements from day 2 indicate lower and more stable particulate concentrations compared with the March 4 experiment. The maximum RESP concentration recorded during day 2 was 0.192 mg/m³, while the average concentration from ignition until the end of the experiment was 0.042 mg/m³.

The day 1 measurements ranged from 0.009 mg/m³ to 4.43 mg/m³, whereas the day 2 measurements ranged from 0.013 mg/m³ to 0.193 mg/m³. This substantial

reduction in both the range and peak concentrations indicates a more stable particulate concentration profile during the second day of testing. The measured RESP concentrations remained well below the occupational exposure limits commonly referenced by Arbetsmiljöverket and OSHA, which are typically in the range of 2.5–5 mg/m³, refer to table 6.3. This can be seen especially during the stabilisation phase when the flap was working along with the stove. However, it should be noted that these limits are intended for occupational and industrial environments and are therefore not directly comparable to residential indoor air quality conditions.

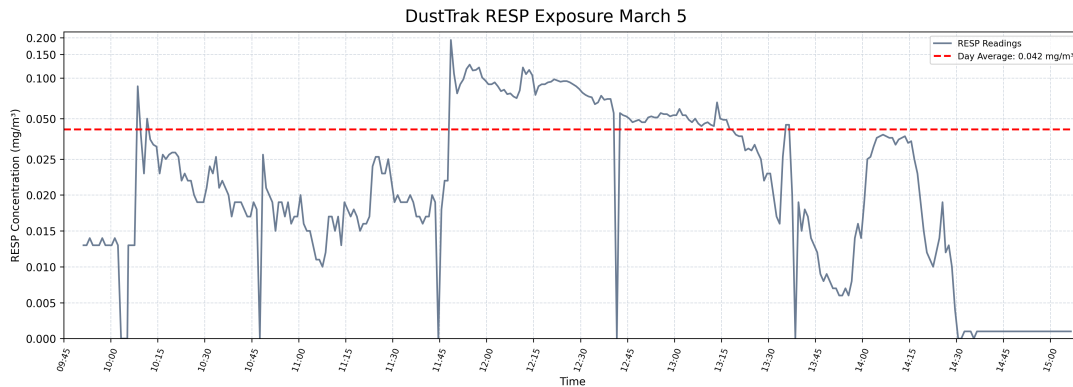


Figure 6.18: RESP Reading for March 5th

Several short duration drops to near-zero RESP concentrations were observed at regular intervals throughout the measurements, likely due to temporary sensor or sampling resets, which are instrument default settings.

6.2.11 Key Findings for Day 2 (March 5th)

Overall, the March 5 experiment demonstrated that the modified opening/flap configuration provided more stable operating conditions compared with the airtight setup tested on March 4. The room maintained lower average pollutant concentrations, improved pressure balance, and more stable airflow behaviour throughout much of the experiment. The results also showed faster thermal response and lower sustained particle accumulation, suggesting that the additional make up air improved both combustion performance and general ventilation behaviour within the room.

However, the experiment also demonstrated that indoor air quality remained strongly influenced by pressure disturbances and combustion related events. Temporary spikes in UFP, PM, TOC volatile organic compound, and temperature were observed during ignition, critical pressure conditions, and positive pressure tests, indicating that pollutant transport within the room was highly sensitive to airflow instability and pressure driven redistribution. The findings therefore suggest that, while the opening/flap system improved overall room behaviour, maintaining stable pressure conditions remains essential for minimizing pollutant accumulation during wood stove operation.

7

Discussion

7.1 Comparison of Static and Movable P-Trak Measurements: Exposure vs Source Behaviour

The observed trend, where the static P-Trak measurements recorded higher concentrations compared to the movable measurements, was consistent across both experimental days. This behaviour is attributed to the difference in measurement approach rather than changes in ventilation conditions.

The static P-Trak, positioned on the table, represents a fixed location where particles accumulate over time due to mixing within the room. As a result, it captures the integrated concentration, including peak events and subsequent dispersion.

In contrast, the movable P-Trak records localized particle concentrations for relatively short durations at specific points near the stove and chimney. These locations are influenced by complex and transient airflow patterns. The immediate vicinity of the stove and chimney is affected not only by smoke escaping from the stove or chimney, but also by fresh air entering the room through the air inlet flap and through gaps around the chimney where it passes through the window board. This incoming air can dilute particle concentrations locally. Furthermore, near the stove, hot combustion gases rise rapidly due to buoyancy, carrying particles upward within the thermal plume. As a result, particles may not remain in the immediate vicinity of the stove for extended periods. Consequently, the movable P-Trak records lower concentrations than the static P-Trak. These observations indicate that proximity to the stove does not necessarily correspond to higher particle concentrations.

Similarly, leakage at chimney joints produces localized spikes however, these are short lived and do not contribute significantly to sustained concentration levels. Over time, particles disperse and mix throughout the room, resulting in a more uniform distribution of ultrafine particles. This mixing process leads to the accumulation of particles at locations away from the immediate source, as observed at the static measurement point.

Therefore, the higher concentrations observed at the static location indicate the overall room exposure level, whereas the movable measurements reflect spatial variability and localized conditions.

7.2 TOC vs CO

The TOC–CO correlation plots shown in figure 7.1 were used to examine the relationship between combustion related organic emissions and carbon monoxide concentrations during stove operation. Since CO is commonly associated with incomplete combustion, while TOC represents the presence of volatile organic compounds released during wood combustion, the comparison provides an indication of pollutant behaviour under different operating conditions.

The overall TOC–CO relationship was similar on both March 4th and March 5th. However, both CO and TOC concentrations were generally lower on March 5th compared with March 4th. March 4th recorded CO concentrations of up to approximately 15 ppm and TOC concentrations exceeding 100 ppm, whereas March 5th exhibited lower overall concentrations with fewer extreme values. Although some scatter was observed in both datasets, indicating that TOC and CO were not directly proportional, the general behaviour remained similar between the two measurement days.

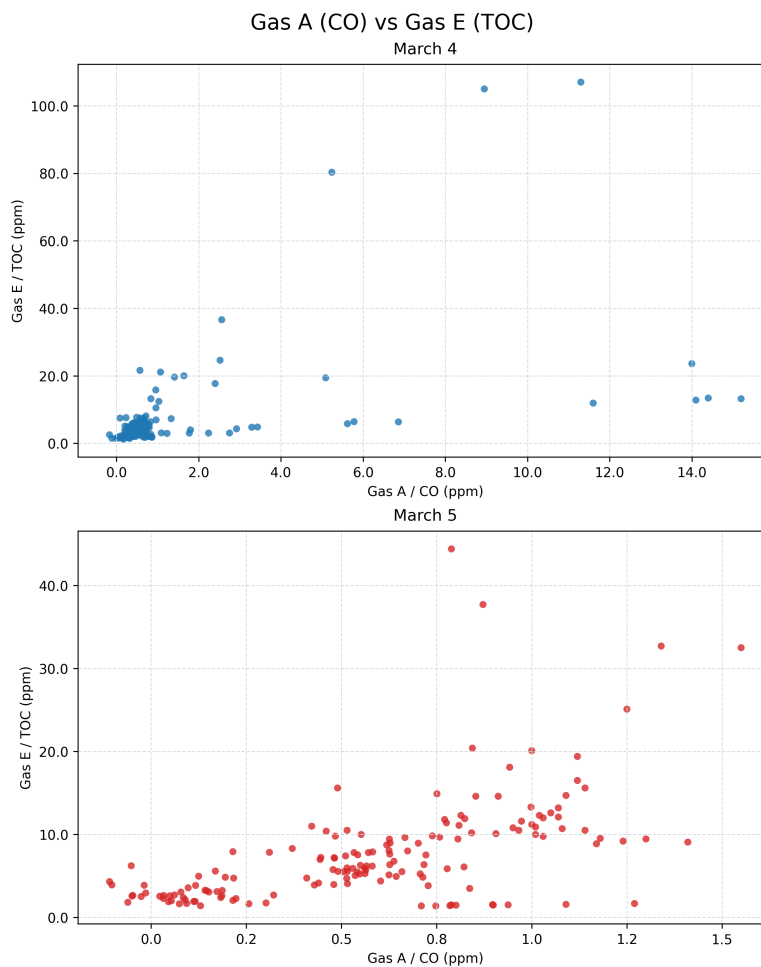


Figure 7.1: TOC vs CO For March 4th and March 5th

The lower pollutant concentrations observed on March 5th are consistent with the

increased air supply provided by the opening/flap configuration. The additional air supply reduced the room underpressure and thereby reduced smoke leakage from the stove and chimney system. As a result, lower indoor concentrations of both CO and TOC were observed compared with the more airtight configuration used on March 4th.

Overall, the results suggest that improving the air supply and reducing underpressure contributed to reduced smoke leakage and lower indoor pollutant concentrations during stove operation.

7.3 CO vs UFP

Correlation analysis between UFP concentration and CO concentration was performed to evaluate whether ultrafine particle emissions were primarily associated with incomplete combustion behaviour or influenced by additional airflow and transport mechanisms. Since CO is commonly used as an indicator of oxygen deficient combustion, comparison with UFP concentrations helps assess the relationship during stove operation.

If UFP and CO increase together, this suggests that particle formation is strongly linked to oxygen deficient combustion. However, if UFP increases while CO remains low or moderate, this indicates that particle behaviour is also controlled by airflow patterns, pressure imbalance, leakage, and redistribution within the room. In that case, the focus should be on pressure regulation, controlled air supply, and preventing backdraft or pollutant re-entry rather than only improving combustion efficiency.

March 4th recorded substantially higher CO concentrations than March 5th, reaching 15 ppm compared with less than 1.5 ppm on March 5. However, the overall CO–UFP relationship was similar on both days refer figure 7.2. While UFP concentrations were higher on March 4th, the increase was not proportional to the increase in CO. This indicates that factors such as smoke leakage and airflow conditions influenced particle concentrations in addition to combustion behaviour. The higher CO levels observed on March 4th are consistent with the increased smoke leakage observed under the airtight room configuration.

The near zero UFP points observed in the March 5th correlation plot are likely associated with the pre-ignition/background measurement period, during which the P-Trak static was not recording, but the stove had not yet begun producing significant combustion related particles. Therefore, these points should be interpreted as baseline indoor particle conditions rather than zero emission during stove operation. Once ignition and combustion started, UFP concentrations increased noticeably.

The red dashed line shown in the correlation plots represents the best-fit line between CO concentration and UFP concentration. The positive slope of the line indicates that UFP concentrations generally tended to increase with increasing CO concentrations, suggesting a positive relationship between incomplete combustion

behaviour and ultrafine particle generation.

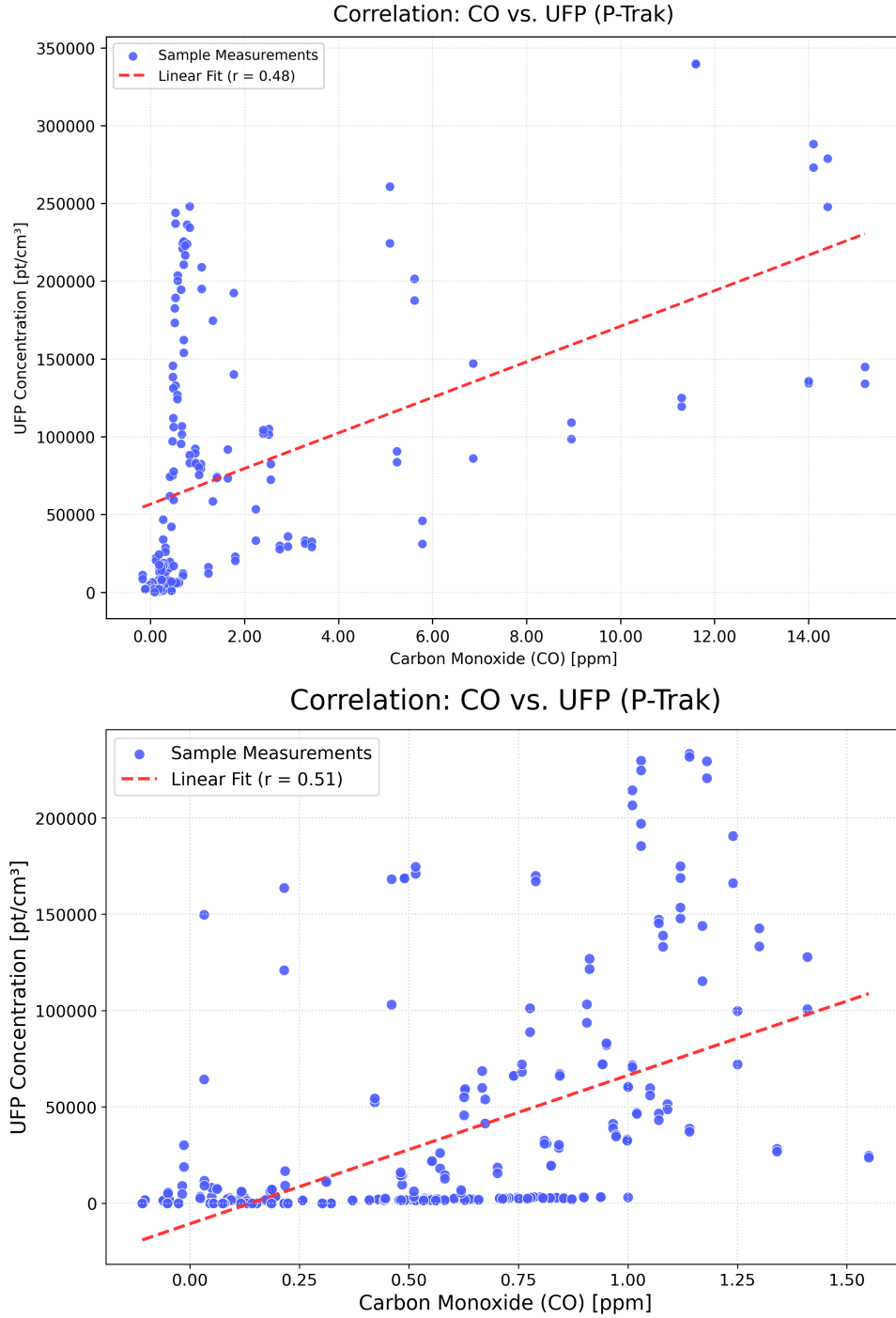


Figure 7.2: CO vs UFP For March 4th and March 5th

The reported Pearson correlation coefficient (r) represents the strength of the linear relationship between the two variables rather than the slope of the line itself. The obtained values ($r \approx 0.48$ for March 4 and $r \approx 0.51$ for March 5) indicate a moderate positive correlation, meaning that CO and UFP concentrations were related but not strongly proportional. This indicates that ultrafine particle generation

was partially associated with incomplete combustion behaviour in both experiments.

The scatter of the measurement points around the line further suggests that UFP behaviour was influenced not only by combustion conditions, but also by additional factors such as airflow patterns, pressure variations, smoke leakage, fuel loading, and pollutant redistribution within the room. Overall, the results indicate that UFP concentrations were affected by both combustion processes and airflow related factors within the experimental setup.

7.4 Consolidated results for day 1 and day 2

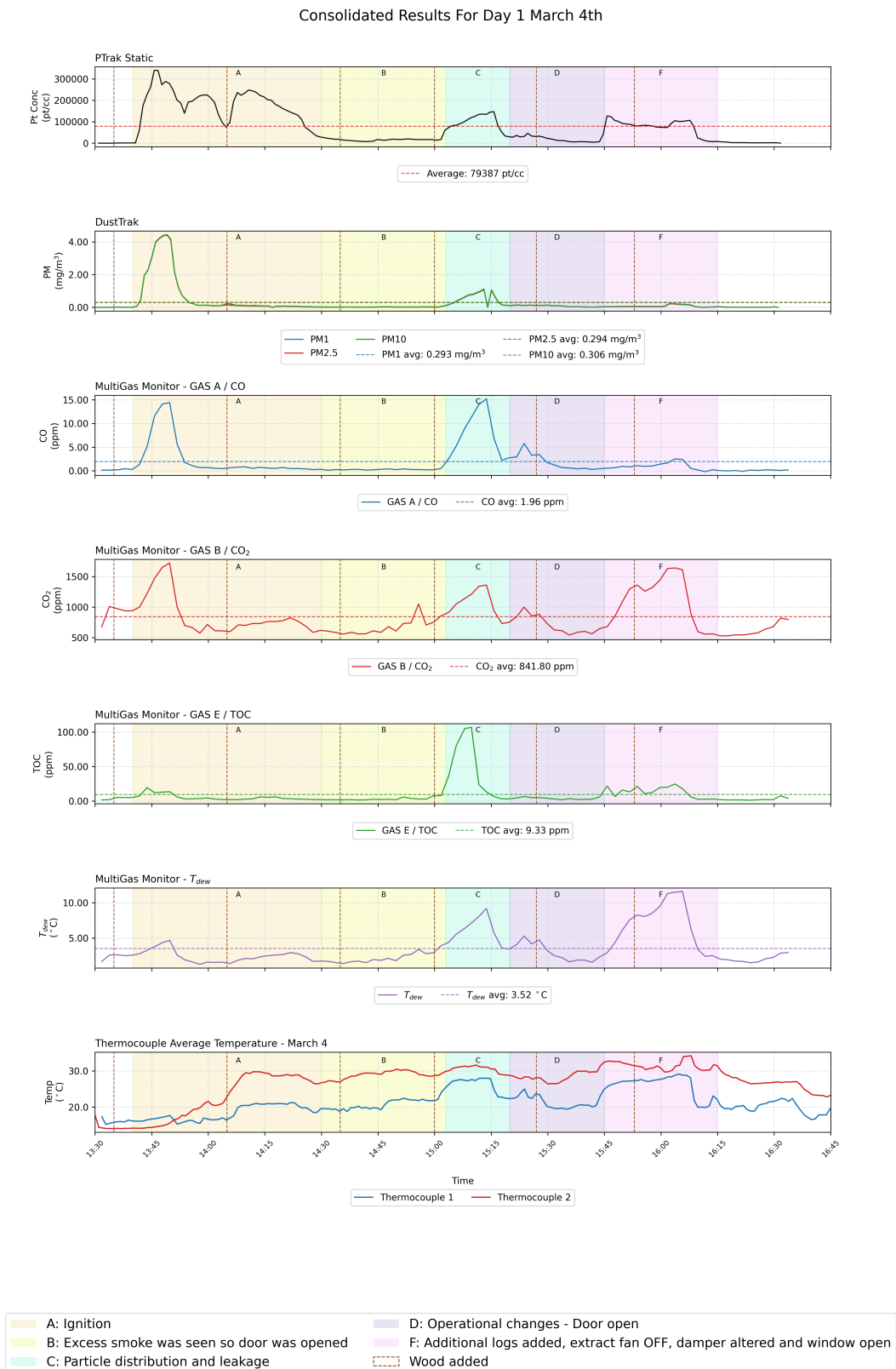


Figure 7.3: Consolidated Results for Day 1 March 4th

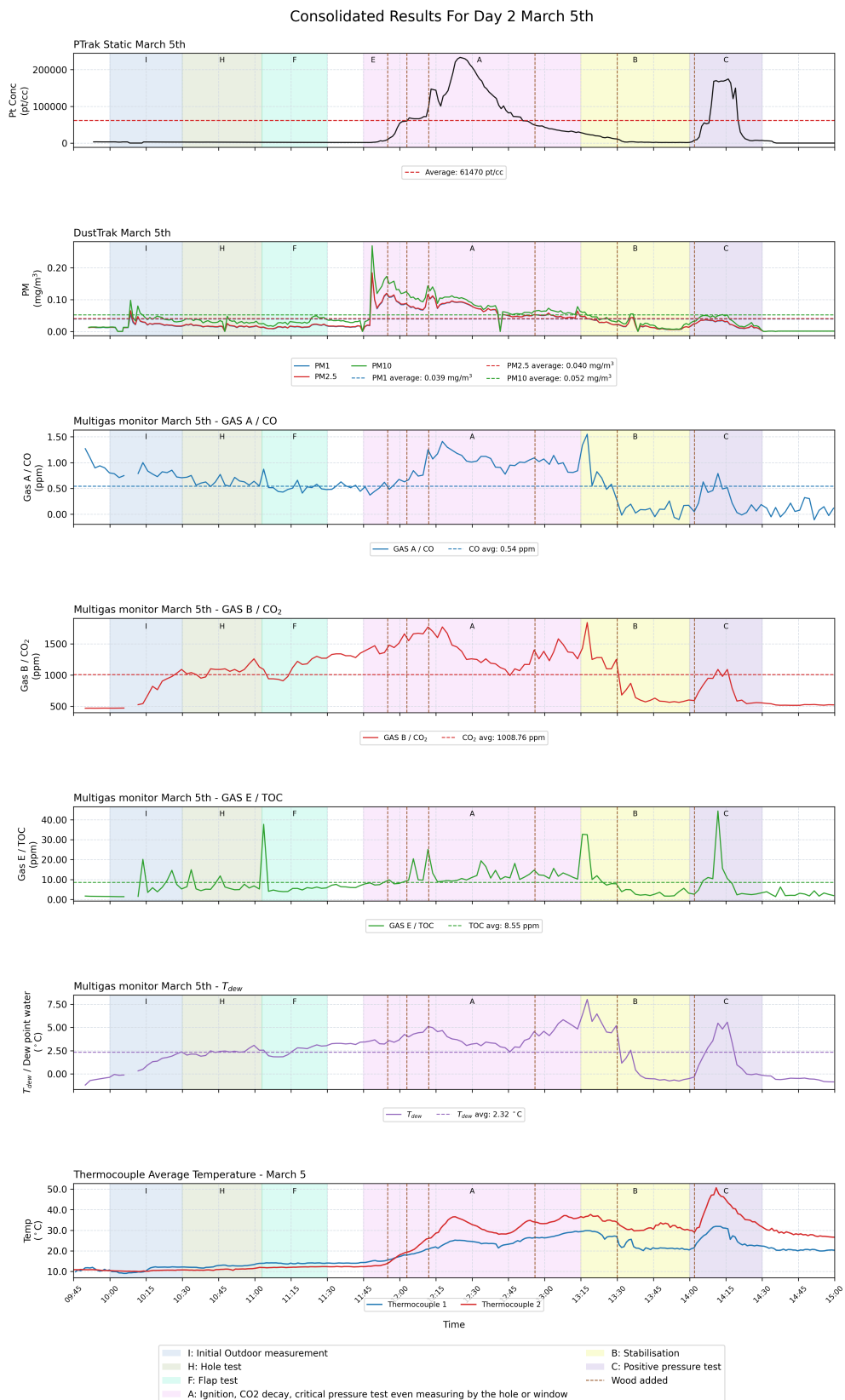


Figure 7.4: Consolidated Results for Day 2 March 5th

8

Conclusion and Future Work

8.1 Conclusion

The experiments conducted over the two day period provided important insight into the assembly, installation, and operational behavior of the temporary wood stove under controlled indoor conditions. The study investigated the interaction between combustion behavior, airflow conditions, indoor pressure variations, and pollutant emissions during stove operation under emergency scenarios.

During the first day of testing, the experiments primarily focused on understanding the influence of underpressure conditions on combustion stability and pollutant behaviour. The results demonstrated that moderate underpressure conditions negatively affected stove performance, resulting in unstable combustion, backdraft, smoke leakage, and elevated particle concentrations.

A key observation from the first day was that the absence of a controlled air inlet resulted in air entering through unintended leakage paths, such as chimney joints and gaps around the chimney wooden board interface. Measurements near the gap around the chimney interface showed comparatively lower particle concentrations, indicating that relatively cleaner air was entering through this location. Combined with the smoke visualization tests, these observations led to the conclusion that introducing a controlled opening or hole near the chimney wooden board interface could potentially provide a more stable and predictable airflow path into the room (refer table 8.1). This finding formed the basis for the second day of testing.

The second day, therefore, focused on evaluating the influence of introducing an opening near the chimney wooden board interface, along with further investigations involving flap configurations, pressure behaviour, and airflow control. The opening tests demonstrated that providing a controlled inlet improved airflow conditions and reduced the reliance on uncontrolled leakage paths. Similarly, flap and damper adjustments showed that airflow resistance strongly influenced room pressure, combustion stability, and leakage behaviour. The experiments also included observations under near neutral and positive pressure conditions, which demonstrated improved combustion performance (refer table 8.1) compared to moderate underpressure conditions.

The results showed that stove performance was strongly influenced by room pres-

sure conditions. During the critical pressure tests, a room differential pressure of approximately -5.8 Pa was associated with increased leakage and elevated ultrafine particle concentrations. However, this value is specific to the room, stove, chimney, and ventilation configuration used in this study and should not be considered a universal threshold. In comparison, conditions closer to neutral pressure resulted in more stable stove operation and lower pollutant accumulation.

As pointed out in chapter 3, the DustTrak may overestimate the PM concentrations refer table 8.1 by a factor of more than 2. This calls for caution when comparing the measured data with guideline values, such as those established by the WHO. However, it appears clear that the overall average value during day 1 widely exceeded the WHO guidelines. This is the case also regarding the peaks measured during both day 1 and day 2. However, the measured overall average day 2, and the average during normal operation day 2 are close to the WHO guideline values. Given the uncertainty of the DustTrak instrument, the true values may well be below the WHO guideline values. All reported average CO concentrations are below the guideline values. No other of the measured substances is subject to any guidelines.

Table 8.1: Summary of average and peak measured quantities for Day 1 (March 4th) and Day 2 (March 5th).

Quantity	Unit	Day 1		Day 2		
		Average	Peak	Average	Peak	Average (Normal Operation)
PTrak Static	pt/cc	79,387	340,166	61,470	233,300	31,575
PM ₁	mg/m ³	0.293	4.420	0.039	0.181	0.049
PM _{2.5}	mg/m ³	0.294	4.420	0.040	0.184	0.050
PM ₁₀	mg/m ³	0.306	4.450	0.052	0.269	0.069
CO	ppm	1.96	15.20	0.54	1.55	0.52
CO ₂	ppm	841.80	3330.00	1008.76	1840.00	1172
TOC	ppm	9.33	107.00	8.55	44.40	8.66
T _{dew}	°C	3.52	11.60	2.32	8.01	2.87

Note: Average values are calculated from the experiment analysis starting from ignition to the end of the experiment phase (13:35 - 16:32) for Day 1, March 4th, and (11:45 - 15:07) for Day 2, March 5th. Peak values are taken from the plotted experiment ranges for each instrument. The Day 2 normal operation averages correspond to measurements obtained during standard operation conditions prior to the experimental phase. Normal Stove operation excluding the critical pressure test and positive pressure test (1:45 - 12:20 and 13:15 - 14:00)

In addition to combustion performance, a few practical challenges related to stove assembly and chimney installation were identified. Difficulties associated with component alignment, sealing, and chimney fitting highlighted the importance of installation quality for maintaining stable airflow conditions and reducing leakage. Overall, the study demonstrated that the temporary stove can operate under emergency indoor conditions. However, its performance is highly sensitive to airflow balance, indoor pressure variations, and available combustion air supply. The findings suggest that improved chimney design, controlled inlet openings, better sealing mechanisms, and optimized airflow control may contribute to improved combustion stability, reduced leakage, and lower indoor pollutant exposure during operation.

8.2 Future Work

The present study provided insight into the relationship between combustion behavior, airflow conditions, indoor pressure variations, and pollutant emissions during the operation of a temporary wood stove under controlled indoor conditions. However, several limitations and uncertainties were identified during the experiments, indicating the need for further investigation. Future work should therefore focus on improving the understanding of airflow behavior, combustion stability, pollutant distribution, and stove performance under more realistic operating conditions.

One limitation of the present study is that the experiments were conducted over a relatively short duration and under controlled indoor conditions. Although the extract fan system allowed simulation of pressure conditions similar to those created by outdoor wind effects, actual environmental conditions are more variable and complex. Future studies should therefore investigate stove performance under different weather conditions, including varying wind speeds, wind directions, and outdoor temperatures. Since the stove is intended for emergency or crisis situations where mechanical ventilation systems may not be available, understanding the influence of natural environmental conditions is particularly important. Wind driven pressure differences may significantly influence chimney draft, airflow direction, smoke leakage, and combustion stability, especially in temporary installations.

Further investigation is also required regarding the influence of fuel characteristics on combustion behavior and pollutant formation. In the present study, birch wood with a moisture content of approximately 18% was used throughout the experiments. However, parameters such as wood species, moisture content, fuel size, fuel arrangement, and fuel loading frequency may significantly influence combustion efficiency, heat release, chimney draft, particle emissions, and carbon monoxide formation. Future work should therefore include a more combustion focused analysis investigating how different fuel conditions affect stove performance under varying pressure conditions.

Although differential pressure and airflow measurements were continuously monitored during the experiments, future studies should include more detailed pressure mapping and airflow visualization techniques. Additional pressure sensors positioned at multiple locations throughout the room and chimney system could improve understanding of localized pressure variations and airflow paths. Similarly, advanced airflow visualization methods may help quantify backdraft, turbulence, and leakage behavior more accurately.

Further work should additionally focus on improving the design of the stove and chimney system. During the experiments, the horizontal section of the chimney consistently exhibited the highest particle concentrations and the greatest indication of leakage. This suggests that chimney geometry plays an important role in airflow stability and pollutant transport. Future studies should therefore investigate alternative chimney configurations, including different chimney lengths, angles, and orientations, in order to improve draft performance and reduce leakage. Improved

sealing mechanisms at chimney joints and stove interfaces should also be investigated, since leakage locations were identified during operation.

Additional investigations should also evaluate stove performance under realistic occupancy conditions. In the present study, the experiments were conducted in a controlled indoor environment with limited occupant influence. However, in real emergency situations such as war, power outages, or temporary shelter conditions, multiple occupants may be present within confined indoor spaces. Human occupancy may influence airflow patterns, thermal comfort conditions, oxygen consumption, and indoor pollutant accumulation. Activities such as door opening, occupant movement, and varying occupancy levels may additionally influence pressure balance and ventilation behavior. Future studies should therefore investigate stove operation in occupied apartments and under realistic occupancy scenarios in order to better understand indoor exposure conditions and operational safety during practical use.

Future work should also investigate the influence of different apartment configurations and building characteristics on stove performance. Factors such as room size, apartment layout, ceiling height, leakage conditions, and building airtightness may significantly affect airflow distribution, pressure behavior, and pollutant transport within the indoor environment. Since emergency conditions may involve temporary installation in different residential environments, evaluating the stove under multiple apartment conditions would provide a broader understanding of its practical applicability.

In addition, future investigations should explore the influence of different flap and damper configurations on airflow stability and combustion performance. The present study demonstrated that airflow resistance and pressure balance strongly influenced leakage behavior and combustion stability. Therefore, evaluating different flap geometries, adjustable inlet openings, and alternative damper configurations may help optimize airflow control within the system. Such investigations could contribute to improved combustion efficiency, reduced leakage, and more stable chimney draft under varying pressure conditions.

Overall, the study showed that stove performance is strongly influenced by combustion conditions, airflow behavior, and indoor pressure variations. The experiments highlighted the importance of stable air supply and pressure balance in reducing leakage and improving combustion stability. However, further investigation under more realistic operating and environmental conditions is required to improve the performance, safety, and practical applicability of the stove system during emergency use. oxygen consumption, and indoor pollutant accumulation. Activities such as door opening, occupant movement, and varying occupancy levels may additionally influence pressure balance and ventilation behavior. Future studies should therefore investigate stove operation in occupied apartments and under realistic occupancy scenarios in order to better understand indoor exposure conditions and operational safety during practical use.

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A

Appendix 1

Testo Profile: March 4

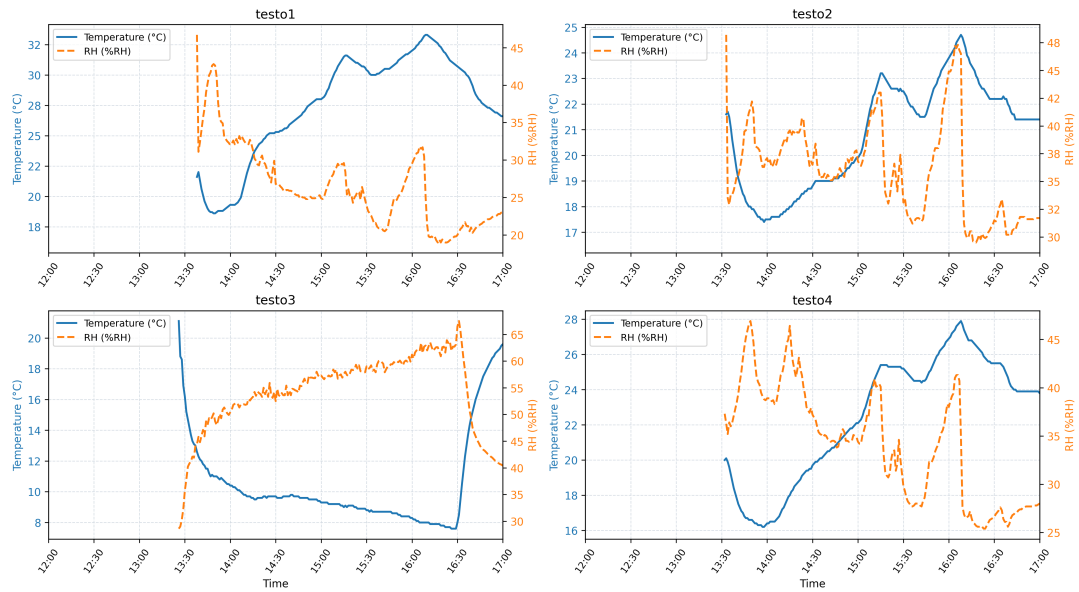


Figure A.1: Testo plot for March 4th

Testo Profile: March 5

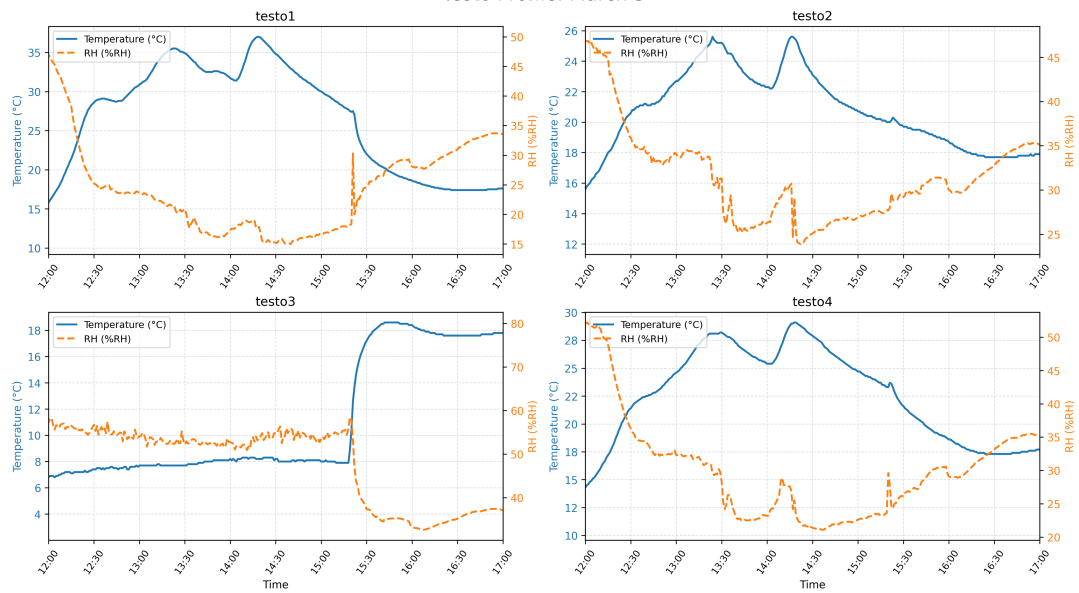


Figure A.2: Testo plot for March 5th

A.1 Interpretation of CO₂ Decay when Stove is switched OFF

In Figure A.3, a distinct decrease in carbon dioxide concentration can be observed during which the CO₂ level decreases from about 2300 ppm to nearly 1000 ppm. This substantial reduction over a relatively short period indicates that the room is able to remove CO₂ efficiently, reflecting effective air exchange between the indoor and outdoor environments.

The observed behaviour suggests that elevated gas concentrations do not remain in the room for extended periods. Due to the elevated levels of ultrafine particles and carbon monoxide, the room was opened, and the extract fan increased. The smooth decay over this interval, which indicates stable airflow conditions within the room. This also suggests that the reduction in CO₂ concentration is primarily governed by natural ventilation, without significant internal airflow disturbances.

Overall, the results indicate that, under stove off conditions, the room exhibits effective and stable ventilation performance, with sufficient air exchange to facilitate the removal of indoor pollutants.

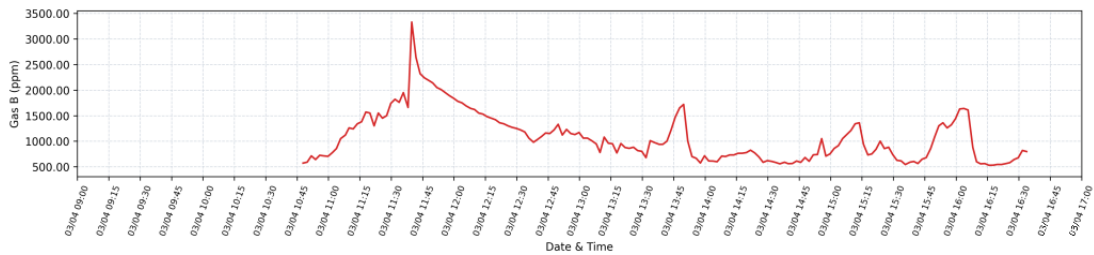


Figure A.3: CO₂ from Multigas Monitor

A.2 Regression Analysis (Stove Switched Off)

The graph below presents the regression analysis of CO₂ decay under stove off conditions. It can be observed that the regression line exhibits a distinct negative slope. Additionally, the data points are closely aligned with the regression line, indicating that they follow a consistent trend with minimal deviation. This suggests that there is effective air exchange within the room and that CO₂ is being removed steadily over time, reflecting good ventilation performance.

However, it should be noted that this regression line is not used for the calculation of ACH. Instead, it serves as a representation of the overall trend by incorporating all data points and reducing the impact of fluctuations. Despite the effective decay of CO₂, elevated ultrafine particle concentrations were still observed during combustion-related activities. This indicates that effective CO₂ removal does not necessarily correspond to effective local particle removal, as gaseous pollutants and ultrafine particles behave differently within the indoor environment.

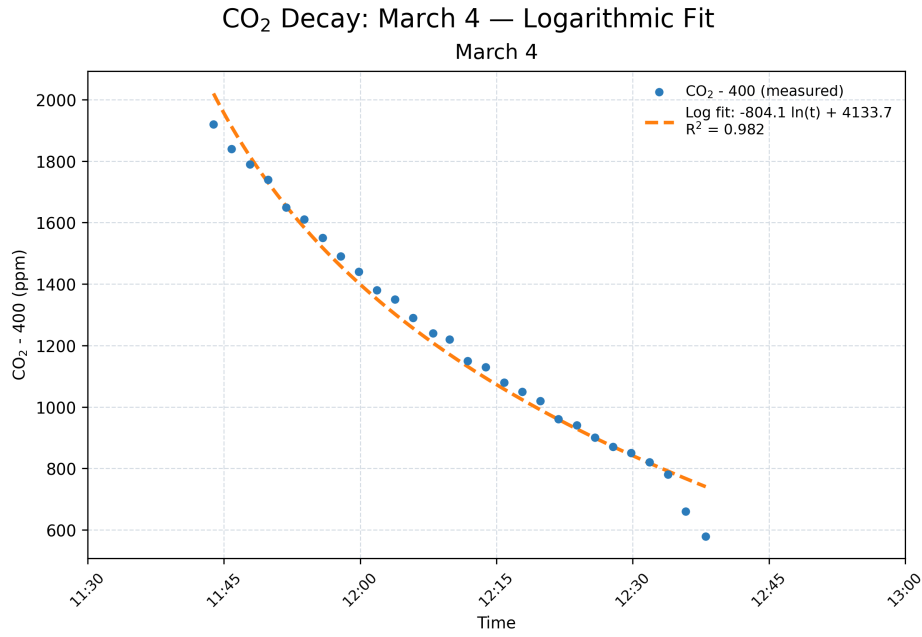


Figure A.4: CO₂ Decay

Although both CO₂ and ultrafine particles are influenced by ventilation and air exchange, their behaviour within the indoor environment differs significantly. CO₂ behaves as a gas and mixes relatively uniformly within the room, resulting in a smoother decay trend over time during ventilation. In contrast, ultrafine particles are not simply gases, but tiny solid or liquid particles generated during combustion. Their movement is additionally influenced by buoyancy driven airflow, turbulence, recirculation, surface deposition, localized leakage, and continuous particle generation from the stove. As a result, while CO₂ concentration decays gradually over time, ultrafine particle concentrations may continue to fluctuate and exhibit localized peaks even under ventilated conditions.

A.3 ACH calculation

A.3.1 ACH Calculation and Ventilation Performance Analysis

The air change rate (ACH) was calculated using the CO₂ decay method under stove-off conditions, since no internal CO₂ source was present and the decay was therefore primarily governed by natural ventilation and air exchange within the room.

ACH was calculated using:

$$ACH = \frac{1}{t} \times \ln \left[\frac{(C_0 - C_R)}{(C_1 - C_R)} \right]$$

Where:

$$ACH = \text{air change rate (h}^{-1}\text{)}$$

$$t = \text{time interval (hours)} = 55 \text{ minutes} = 0.916 \text{ hours}$$

$$C_0 = \text{initial indoor CO}_2 \text{ concentration} = 2320 \text{ ppm}$$

$$C_1 = \text{final indoor CO}_2 \text{ concentration} = 979 \text{ ppm}$$

$$C_R = \text{outdoor/background CO}_2 \text{ concentration} = 400 \text{ ppm}$$

Substituting the values:

$$ACH = \ln \left[\frac{(2320 - 400)}{(979 - 400)} \right]$$

$$ACH = \ln(3.31)/0.916$$

$$ACH = 1.306 \text{ h}^{-1}$$

The corresponding ventilation flow rate was determined using:

$$Q = ACH \times V$$

Where:

$$Q = \text{ventilation flow rate (m}^3/\text{h)}$$

$$V = \text{room volume (m}^3\text{)}$$

The room volume was calculated as:

$$V = 2.8 \times 4.2 \times 2.4$$

$$V = 28.22 \text{ m}^3$$

Therefore:

$$Q = 1.306 \times 28.22$$

$$Q = 36.87 \text{ m}^3/\text{h}$$

The calculated ACH of 1.306 h^{-1} indicates that, under stove off conditions, the room air was exchanged at an average rate of approximately 1.306 room volumes per hour.

A.3.2 Comparison with Swedish BBR Requirements

The Swedish BBR specifies a minimum outdoor airflow requirement of 0.35 L/s per m² for residential buildings.

The floor area of the room was:

$$A = 2.8 \times 4.2$$

$$A = 11.76 \text{ m}^2$$

Thus, the corresponding BBR reference airflow becomes:

$$Q_{BBR} = 0.35 \times 11.76$$

$$Q_{BBR} = 4.12 \text{ L/s}$$

Converting to hourly flow:

$$4.12 \times 3.6 = 14.82 \text{ m}^3/\text{h}$$

The equivalent ACH corresponding to the BBR minimum airflow is:

$$ACH_{BBR} = \frac{14.82}{28.22}$$

$$ACH_{BBR} = 0.53 \text{ h}^{-1}$$

The measured ventilation flow rate of 36.87 m³/h and ACH of 1.306 h⁻¹ are therefore higher than the BBR equivalent minimum reference values.

In Swedish residential buildings, ventilation systems are commonly designed around these minimum requirements, and typical residential ventilation rates are often around 0.5–1 ACH under normal operating conditions. The measured value in this study is therefore relatively high compared to typical residential background ventilation rates. However, the investigated room was a relatively small experimental enclosure operated under mechanically controlled extraction conditions, meaning that the imposed airflow had a stronger influence on room pressure and airflow behaviour than would typically occur in larger residential spaces.

Although the measured ACH exceeded the BBR equivalent minimum reference value, this does not necessarily imply effective local pollutant removal during stove operation. ACH represents a bulk ventilation metric describing the total volumetric air exchange within the room, but does not fully capture localized airflow behaviour, buoyancy driven plume movement, leakage pathways, turbulence, recirculation, or pressure driven transport near the stove and chimney.

Therefore, the results indicate that ventilation quantity alone is insufficient to fully evaluate indoor air quality during stove operation. In addition to overall ACH, factors such as airflow distribution, pressure balance, local leakage, and pollutant transport mechanisms must also be

A.4 CO₂ Decay - March 5th

A.4.1 Interpretation of CO₂ Decay with Stove in Operation

The CO₂ decay observed in the graph (Figure A.5 from 12:15pm to 12:45 pm) indicates an overall reduction in carbon dioxide concentration over the measurement period following the initiation of the decay test. This decreasing trend confirms that air exchange was occurring within the room. However, the decay curve is not entirely smooth, as minor fluctuations can be observed in the form of small increases and decreases in concentration.

These fluctuations may be attributed to several factors. Primarily, the operation of the stove introduces airflow variations due to thermal buoyancy and enhanced air mixing, which can lead to transient changes in local CO₂ concentration. Additionally, measurement related factors may have contributed to these variations. The multigas monitor used for CO₂ measurement may be sensitive to rapid changes in concentration or influenced by localized air conditions surrounding the sensor. Minor sensor related uncertainties or measurement noise may also have affected the recorded values.



Figure A.5: CO₂ Decay Curve Measured Using Multigas Monitor

Despite these fluctuations, the overall decreasing trend in CO₂ concentration aligns with the expected behaviour of a decay process, indicating that the system is functioning as intended in terms of air exchange. Furthermore, the regression analysis in the figure given below of CO₂ concentration over time shows a negative slope, confirming a continuous reduction in concentration and, consequently, the presence of effective air exchange between the indoor and outdoor environments. This regression shows the general decay behaviour but is not used for ACH calculation since combustion is involved.

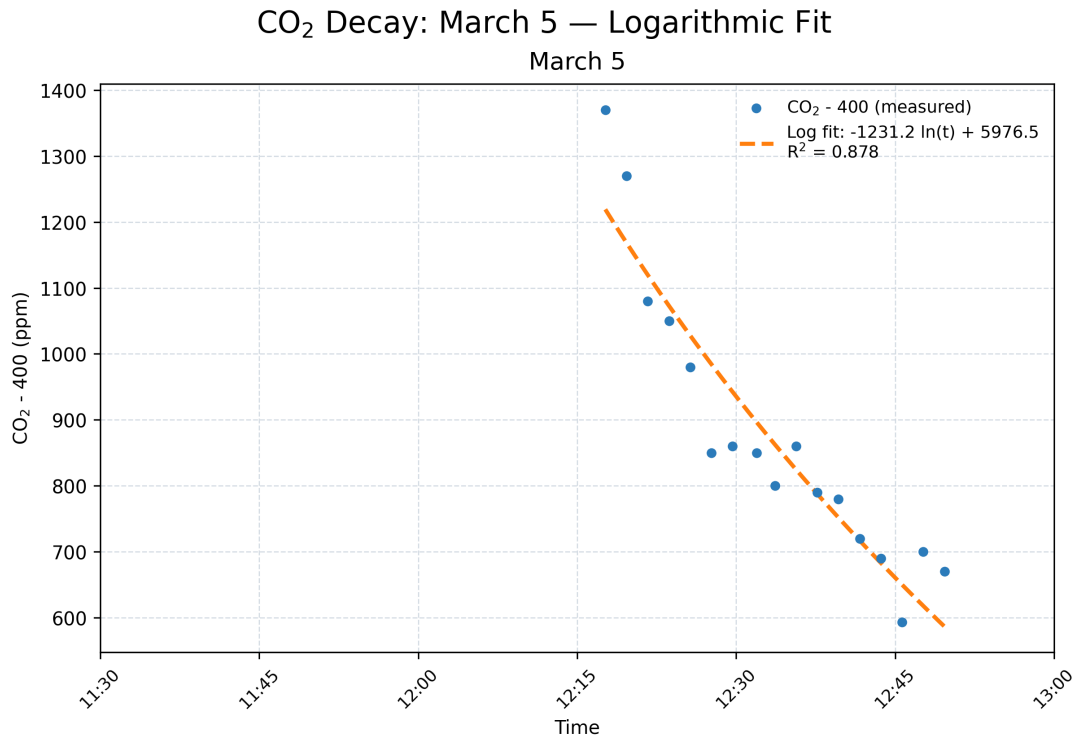


Figure A.6: Logarithmic graph of the CO₂ decay over time

A.5 Time Interval of Measurement Instruments

Table A.1: Measurement instruments and parameters used in the experimental setup

Device	Quantity	Measurement	Unit	Time Interval
Testo Thermo-couple Temperature Sensor	2	Temperature	°C	1 min
Testo 174H Temperature Logger	4	Temperature, Relative Humidity	°C, %	1 min
Rotronic CP11	1	Temperature	°C	—
TSI PTrak UPC	2	Ultrafine particles (UFP)	pt/cc	1 min
Brüel & Kjær Multi-Gas Monitor	1	CO ₂ , CO, TOC	ppm	2 min
DustTrak DRX Aerosol Monitor	1	PM ₁ , PM _{2.5} , PM ₁₀	μg/m ³	1 min

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