STUDY OF HEAT PUMP DRYING SYSTEM

LIM WAN LYNN

A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Mechanical Engineering

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

May 2020

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature :

Name : Lim Wan Lynn

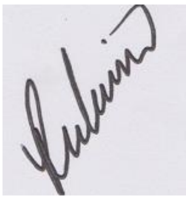
ID No. : 16UEB04374

Date : 15 May 2020

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"STUDY OF HEAT PUMP DRYING SYSTEM"** was prepared by **LIM WAN LYNN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Mechanical Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature	:	
Supervisor	:	Dr. Rubina Bahar
Date	:	15 May 2020

Signature	:	N/A
Co-Supervisor	:	N/A
Date	:	N/A

ACKNOWLEDGEMENT

I would like to thank everyone who has helped me complete this project successfully. The endless guidance and advice of all parties that are close up or far away was the reason for this achievement. Most of all, I have great gratitude and appreciation for my project supervisor, Dr. Rubina Bahar for her limitless assistance. She had been patient and has provided counselling for all my inquiries of the project. She made sure that my project was carried out in the right direction to reach the goals it.

Also, my parents and friends have given me great support and comfort through my struggles and stressful times of the project. My parents gave me strength and warmth to fulfil this project. My friends gave me updates and alternatives to certain problems during my project.

ABSTRACT

Drying clothes outdoor is slowly becoming an obsolete option as more people are living in condominiums and sunlight reaching the drying area is not sufficient. The urbanized living soon may require a clothes dryer as essential household equipment. The major problems with the commercial clothes dryer are the high power consumption and the possible damage to the environment. Hence, this project aims to mitigate these issues with an eco-friendly heat pump clothes dryer. The heat pump principle is derived based on the waste heat that comes out from the condenser side of the indoor air conditioner units. The heat pump clothes dryer utilizes waste heat from the air conditioner to dry clothes, so no extra heat is produced and no electricity is needed to run it. A portable air conditioner, rather than a split unit air conditioner, is used in the project. The air properties were measured to assess the shift in drying properties. The study proves the application of heat pump clothes dryer as a replacement for the current drying methods. It can dry faster by approximately 3 hours compared to outdoor drying at the balcony. It also shows the impact of temperature setting for the portable air conditioner on the drying time of clothes. The users will not face a significant difference in the drying time of 1.5 hours for 1 kg of clothes when they change the temperature setting throughout the day. The suitable clothes load for the heat pump clothes dryer was attained to note the strength of the heat source supplied from a portable air conditioner. The users can dry up to 1.5 kg of clothes for over 3 hours. The users may need to use the dryer more frequently or a longer time to clean their weekly laundry load if they switch on the portable air conditioner for a shorter time. Also, the study exhibits that the drying rate will be much faster when the inlet is completely sealed rather than partially sealed. The target of this study ultimately is to evaluate the performance of such a drier and analyze its potential as a competitor to the commercial clothes dryer.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

COP_{AC}	Coefficient of performance for air conditioner
$\dot{m}_a$	Dry air mass flow rate
$\dot{m}$	Drying rate, kg/hr
m_i	Mass of clothes after spin dry in washing machine, kg
m_f	Mass of clothes after dry, kg
h_1	Enthalpy at the inlet of evaporator
h_2	Enthalpy at the outlet of evaporator
W_c	Heat release from condenser
W_f	Power consume by auxiliary fan
ω_1	Specific humidity of air at the inlet
ω_2	Specific humidity of air at the outlet
v	Specific volume of air at inlet, m^3/kg
Δt	Time, hr
A	Area of the inlet, m^2
ICPT	Imbalance Cost Pass Through, sen/kWh
Q	Heat transfer in the evaporator
RAC	Residential air conditioner
RH	Relative humidity
SMER	Specific moisture extraction rate, kg/kWh
V	Velocity of air at inlet, ms^{-1}
W	Work supply to the air conditioning system

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Drying clothes outdoors is a traditional method and strongly influenced by weather conditions. The clothes absorb heat energy from sunlight, which causes the water in the fabric to evaporate. On non-sunny days, the clothes will only dry by the blowing wind. The drying rate depends on the humidity of the air, the surface area of clothes, and external factors (i.e. Wind flow, Sunlight, Surrounding temperature). The evaporation of moisture content will increase humidity in the surrounding. The humidity of air has a more significant effect on the drying rate compared to the temperature. Wind flow causes a better evaporation rate compared to sunlight. This is because the wind helps air circulation and continuously removes high moisture content air. Nowadays, individuals and families are searching for other methods to dry their clothes faster and during various weather conditions. New mechanical machines like clothes dryers were developed for this function, and it is an energy-intensive method that requires a high amount of heat for drying.

1.2 Importance of the Study

As cities develop and more buildings become skyscrapers, taller buildings will block the sunlight from reaching shorter buildings and lower floors will not have enough sunlight into their unit. Based on Figure 1.1, buildings of the same height require a shorter distance for sunlight to reach the lowest floor of the building. A taller building blocks sunlight from reaching shorter buildings so a larger gap between them is needed as shown in Figure 1.1. Even at noon when the sunlight is the brightest, it may not be direct at certain parts of the building. Sunlight is essential as heat from the Sun is used to dry clothes. Small condominium units have a balcony to dry clothes but in most cases, the clothes may not get enough sunlight to dry it. If clothes remain damp and take too long to dry, it will smell musty as mould spores and bacteria may grow. The drying chamber protects clothes from insects, rain and bad smells from cooking or fogging. This may affect the condition of fabric in terms of colour or texture so clothes need to dry until moisture is gone by heating for a sufficient amount of time.

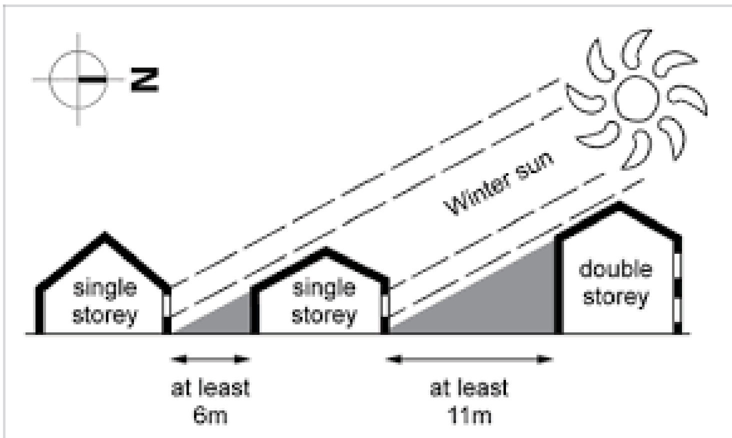


Figure 1.1: Comparison in Reach of Sunlight for Shorter and Taller Buildings (Source: Yourhome.gov.au, 2019)

In consequence, more people start to purchase clothes drying cabinets that will produce no crease and non-musty smell in the clothes. Dryers also are used when clothes need to be dried between a short time. The drying cabinet prevents the clothes from absorbing the haze and exhaust gas from cars. It is quite common for people to use their air conditioner throughout the day in several countries that are hot all around the year. This study propose to use the waste heat from the outdoor unit to dry clothes rather than dispersing it to the surrounding. Flanner 2009 states that waste heat contributes 0.028 W/m^2 to climate change, which is roughly 1% of global warming (John, 2010). Even though it is a relatively small amount of climate change compared to other greenhouse gases, but as the society uses more technology and mechanical mechanism, there will be more waste heat released to the environment. Climate change has become an environmental concern that tackled by various fields.

Especially during the rainy seasons and on cloudy days, it is difficult to dry clothes outdoors because there is no sunlight and it is very humid. Outdoor clothes drying depends on the weather and season. The heat released from people, appliances, and lights is removed by air conditioning and used to dry clothes. When this study design a clothes dryer, it should consider the frequency of drying clothes, types of clothes wash, space constraint, cost and weather. The clothes dryer design must be able to wash difficult-to-dry fabrics (i.e. cotton, wool), as it will retain the moisture longer. Hence, this study should compare the drying process of several types of clothes dryers to test the efficiency, cost-effectiveness and convenience of the prototype.

1.3 Problem Statement

Clothes dryers consume a lot of electric energy to heat and remove the moisture in the clothes. Excess heat and moisture disposed from the clothes dryer to room will cause a larger workload on the air conditioner. The drying process of clothes is sped up significantly but it will consume a large amount of electricity. Based on a New Straits Times report, a research firm expect that the Imbalance Cost Pass-Through (ICPT) surcharge will be 1.35 sen/kWh from January to February and rise to 2.55 sen/kWh from March to June (Nst.com.my, 2019). The price of electricity is estimated to continue to increase and become a burden to each house whole.

The current clothes dryer consume a lot of energy because of the heating mechanism that is used to evaporate moisture from the fabric of the clothes. Waste heat is collected by the air conditioner and release to the surrounding. So, rather than just releasing it to the environment and contribute to global warming, this research work aims to use this waste heat for drying clothes. It creates an energy-saving solution, which will appeal to the global market as a product that uses renewable energy resources.

Aside from the importance of having a product that is eco-friendly and energy-efficient, the design should be ergonomic. The convenience of handling and keeping the product is crucial to users. If it is difficult to assemble because of many parts, some people may find it troublesome and difficult to construct. The current clothes dryer are a large rectangular shape that cannot be removed and will permanently occupy a space. The condominium units have a small balcony so tenants will not want large clothes dryers that occupy a lot of space.

1.4 Aims and Objectives

People want to go to work, the gym or just get some groceries but their clothes are still wet. They don’t want to spend so much money on a high-powered gadget that will consume a lot of space. This study looks into a replacement method for drying clothes which is greener, sustainable, energy and cost-saving that aligns with Sustainable Development Goals. Thus, this study has the aim of “To provide a sustainable alternative to clothes dryer by studying the heat pump clothes dryer.”

Several objectives were established to become the guideline of this report. The following are the four objectives of the project and purpose o report:

(i) Analyze the waste heat from an outdoor unit of an air conditioner.

(ii) Design a heat pump drier system.

(iii) Fabricate a simple prototype of a heat pump drier system.

(iv) Evaluate the performance of the prototype heat pump drier system.

1.5 Scope and Limitation of the Study

The following Table 1.1 shows the work scope and activities to achieve each outcome:

Table 1.1: The Work scope for Each Objective

Objective	Work scope
Analyze the waste heat from an outdoor unit of an air conditioner	– To identify the sources of heat pump waste heat that can be used in driers. – To identify a suitable drying process compatible with the waste heat source. – To analyze the drying process measuring the psychometric parameters.
Design a heat pump drier system	– Create a suitable heat pump drier system according to space limitation and for convenience of users. – Analyze the effect of design on the efficiency of the air conditioner.
Fabricate a simple prototype of a heat pump drier system	– Prepare the required components to test the design of the heat pump drier system. – Test the performance of design
Evaluate the performance of the prototype heat pump drier system	– Test run of the prototype. – Collect data and analyze the performance.

The limitation depends on several factors as stated in the following Table 1.2:

Table 1.2: The Limitation of Study

Limitation	Reason
Performance of air conditioner	Even if the clothes dryer designed has good performance and reliability, the actual drying rate may not be as effective as it varies with the performance of the air conditioner. The type of air conditioner used by the users cannot be controlled.
Weather condition	The waste heat absorbed from the rooms varies indirectly with the weather condition. The drying rate is indirectly influenced by the surrounding temperature. The weather condition is not predictable.

1.6 Contribution of Study

This study encourages an eco-friendly method of a clothes dryer, which is a heat pump clothes dryer. It utilizes waste heat from the air conditioner's condenser to dry clothes and does not require any power to run. So, it reduces the consumption of electricity as it aims to replace the high powered clothes dryer.

Besides that, this study involves sustainable engineering by planning and developing the project to preserve the environment. Sustainable Development Goals no. 12 states that consuming and producing should be done responsibly. Hence, this study creates a clothes dryer that uses an alternative heat source (Waste Heat) rather than generating heat. This design consumes waste as it uses waste heat and does not create waste due to electric consumption.

Also, this study improves heat pump clothes dryer by changing the design and testing it differently. This study has a variable of using a portable air conditioner, unlike other research that uses a split unit air conditioner. The design has to improve until it can be sold and compete with other clothes dryer products.

1.7 Outline of the report

This is a study of heat pump clothes dryer that uses heat supply from a portable air conditioner. The function of a heat pump clothes dryer was introduced to create a basic understanding of the technology. The available clothes dryers also were studied to know their specifications and understand customer preferences. The air and drying properties were analyse using calculation and Psychometric Chart. The experiment tests the improved heat pump clothes dryer that was designed with various variables to verify its performance. The drying properties were obtained for different drying methods, temperature setting and clothes load. So, the advantages and disadvantages of the commercial and heat pump clothes dryer can be discussed and deduce if it can be a practical alternative of the current clothes dryer.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Before creating a prototype design, the functional principle and available products in the market must be fully grasped to develop the heat pump clothes dryer technology to an advance level. The current products allow us to map out the customer requirement and translate it into product specifications. This section also evaluates the various eco-friendly clothes dryer methods to understand the different approach and their flaws. Previous research on heat pump clothes dryer is another area of study that must be done so the same research is not repeated and help decide the improvement of design. The drying process is the main process that occurs in the clothes dryer and has a high influence on the performance of it. It is vital to focus on getting detailed knowledge of airflow and air properties using formulation and computation.

2.2 Working Principle of Clothes Dryer Design

The heat pump clothes dryer works along with the air conditioner system. The air conditioner absorbs heat from the room and releases it to the clothes dryer through the outdoor unit as shown in Figure 2.1. The heat is transferred from the low-temperature region to the high-temperature region with the operation of the air conditioning mechanism. It uses a refrigerant substance to store and removes the heat energy. Based on Figure 2.1, the following is the flow of heat in the air conditioning cycle to the clothes dryer:

(i) The evaporator (indoor unit) draws the hot air from the room, and the evaporating refrigerant absorbs this heat to turn into the gaseous state.

(ii) Next, the refrigerant passes through the compressor to create a hot and pressurize gas by compressing.

(iii) The condenser condensates hot gas into a cold liquid by metal fins. The refrigerant's phase change cause heat to dissipate into the clothes dryer.

(iv) Finally, the refrigerant flows through the expansion valve and back to the evaporator. It is used to control the refrigerant flowing to the evaporator.

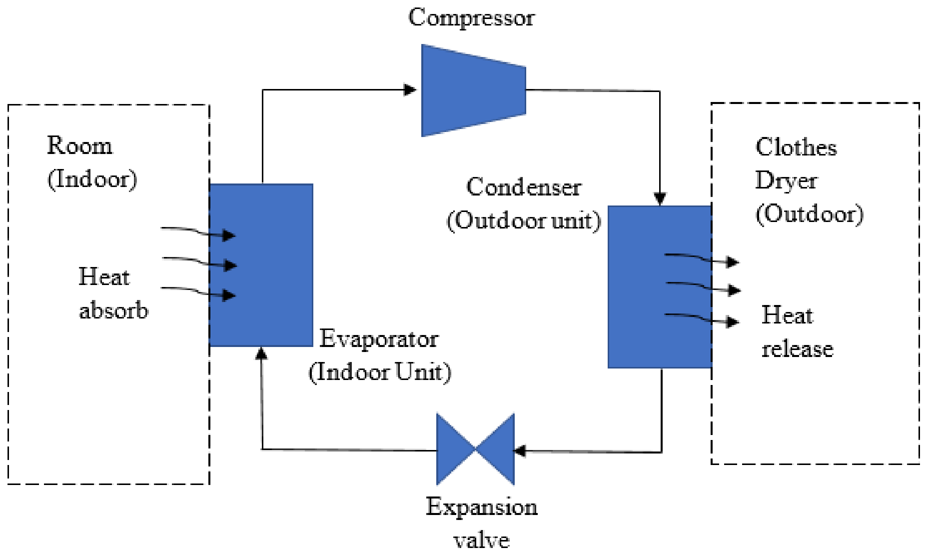


Figure 2.1: Working Principle of Air conditioning with Clothes Dryer

The air conditioner makes the area cool by removing heat whereas the heat pump makes an area hot by absorbing heat. Hence, the clothes dryer design is called heat pump clothes dryer because heat absorbs from a room is used to dry clothes. The clothes dryer is secure at the condenser to accept the flow of hot air accumulated. When appliances and lights are utilized, it releases heat to the surrounding of the room. The activities of human from breathing, running, walking and sitting cause the dissipation of heat and humidifies the room. The walls, windows and basement floor to the ground will absorb heat from the Earth and Sunlight, which will radiate to increase the temperature of the room. An air conditioner operates more frequently and all this waste heat can be collected to evaporate the moisture in fabrics for drying of clothes.

2.3 Types of Energy Saving Clothes Dryer

2.3.1 Solar Clothes Dryer

Solar Clothes Dryer is a different method from the normal way of drying under the Sun. Rather than direct exposure to sunlight, the clothes are dried by indirect sunlight. The heat energy for evaporation of moisture comes from solar radiation. These dryers usually incorporate solar panels to absorb ultraviolet rays for solar energy and the extra heat from sunlight flows to a dryer cabinet. This method requires no electric energy and eco-friendly at the same time able to harvest energy.

Based on Figure 2.2, it shows the basic components and airflow in a solar clothes dryer. Sunlight falls on to the black surface, which is solar collectors. This caused heat to radiate and it is picked up by the air flowing from the bottom. This hot air goes into the drying box, which is a closed system. The drying rate depends on the temperature and volume of air that circulates in the drying box.

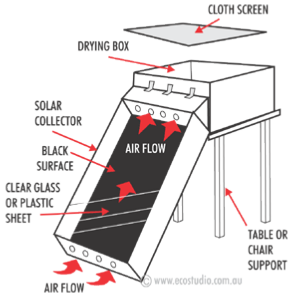


Figure 2.2: Basic Solar Dryer (Source: Climatetechwiki.org, 2019)

2.3.2 Heat Pump Clothes Dryer

Conventional tumble dryer heats the air to dry the clothes and release the extra heat to the surrounding, inversely, the heat pump tumble dryer circulates the hot air to be reuse for drying (Beko.co.uk, 2019). The drying mechanism uses a heat exchanger system to circulate the air for better energy efficiency as shown in Figure 2.3. Thus, the drying chamber does not need to be heated as much because the heat will be reuse.

Hot air enters the drying chamber to evaporate and absorb moisture from clothes. Air flows into the evaporator to condense moisture and removed into a container. There will be a drop in the temperature of the air, so it is reheated and continue to pass through the drying chamber. This heat exchanger system will remove moisture in the chamber and reheat hot air to speed up drying rate and reduce power consumption.

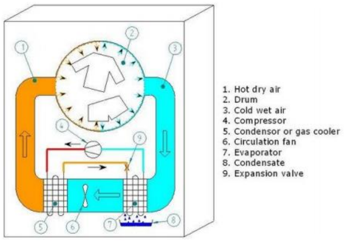


Figure 2.3: Heat Pump Clothes Dryer (Source: Yourhome.gov.au, 2019)

2.3.3 Ultrasonic Clothes Dryer

The clothes' fabrics are dried using vibrational energy in this method, which creates an unstable liquid-air region. The high-frequency vibration will mechanically remove moisture from a wet fabric with the aid of piezoelectric transducers. The ultrasonic excitation forces will develop surface tension to vibrate the water molecules for removal of dampness in fabric. The moisture evaporates to form a cold mist, and it is removed by the circulating air stream in the drying chamber. The transducer generates vibrational energy to eject the water from very damp fabrics. Thermal energy forms when the water molecules are trap in tiny fabric pores because of viscous losses. This method has an efficiency of five times more and faster by two times compared to a conventional clothes dryer when drying cotton fabrics (Ultrasonic Technology Solutions, 2019).

2.4 Work done in Heat Pump Clothes Dryer

The prototype designed will be attached at the outlet of the condenser, so it will directly or indirectly affect the efficiency and performance of the air conditioning system. Fresh air cannot flow through the system as freely as before. The air conditioner will not cool the room as much as before and may cause discomfort to users if the design for the dryer does not consider the optimum dimension and flow characteristics. A fully enclosed drying chamber is good as it traps heat and prevents heat loss to the surrounding but it does not let moisture to leave the chamber.

The performance of the air conditioner can be evaluated by calculating the coefficient of performance (COP_{AC}). The formula used to define the COP_{AC} is:

$$COP_{AC} = \frac{Q}{W} \quad (2.1)$$

where

Q = Heat transfer in the evaporator

W = Work supply to the air conditioning system

COP_{AC} drops by 17.82% after the drying chamber covers the outlet of the condensing unit (Suntivarakorn et al., 2009). The drying chamber blocks and becomes an obstacle at the condensing unit from allowing sufficient heat transfer. The performance of air conditioning operation will reduce in consequence of lack of ventilation and airflow into the system. Hot air stays within the drying chamber and lingers at the outlet of the condenser.

The research by Suntivarakorn et al. studied the difference in drying rate of natural and mechanical ventilation in the drying chamber. The natural ventilation condition was carried out by puncturing holes in the drying chamber until it has the same COP_{AC} as the initial condition. The results show that attaching the auxiliary fan will speed up the drying rate as it helps circulate the hot air in the drying chamber and draw out the moisture. Small power consumption is required to start the fan, but it allows shorter drying time.

Waste heat enters the drying chamber through a duct. Each part of the clothes cannot be exposed to heat because of the nature of hot air to rise and clothes obstructing the flow of hot air. The multiple inlets of waste heat into the drying chamber provides better drying performance compared to a single inlet (Ambarita et al., 2016). The single inlet flows waste heat from the bottom of the drying chamber whereas the multiple inlets have an inlet at the bottom and top. In this way, the hot air can flow from the bottom and top of the clothes and evaporate more moisture from each part of it.

In another research by Ambarita et al., the performance of a conventional heat pump clothes dryer and heat pump clothes dryer using waste heat from a residential air conditioner (RAC) was investigated and compare. The drying rate of clothes and specific moisture extraction rate (SMER) of the drying chamber defined and compared between both conditions to assess the performance and effectiveness of the drying method.

SMER [kg/kWh] is defined with the following equation:

$$SMER = \frac{\dot{m}}{W_c + W_f} \tag{2.2}$$

where

W_c = Heat release from condenser

W_f = Power consume by the auxiliary fan

Drying rate, ṁ [kg/hr] of the clothes is defined with the following equation:

$$\dot{m} = \frac{m_i - m_f}{\Delta t} \tag{2.3}$$

where

m_i = Mass of clothes after spin dry in the washing machine, kg

m_f = Mass of clothes after dry, kg

Δt = Time taken to dry the clothes, hr

The conventional heat pump dryer gives a higher drying rate compared when using waste heat of RAC (Ambarita et al., 2017). The source of heat to dry the clothes is from a heater and the condenser of the air conditioner system. The heat supplied by the heater is uniform and higher temperature compared to waste heat. Unlike the heat draw from the room, which varies depending on the weather and temperature of the room. However, SMER from waste heat of RAC is higher that means the moisture removed from clothes consumes less power. The heat pump dryer using waste heat has a better performance compared to the conventional one.

2.5 Market Analysis of Clothes Dryers

The following are a few types of clothes drying products available in the market. The product specification was referred to as the Lazada product list.

Table 2.1: List of Clothes Dryer in the Market

Product Name	Price (RM)	Power Consumption (W)	Load Weight (kg)	Time to dry (hrs)	Method
Samsung Front Load Combo with Eco Bubble: WD80K6410OW/FQ 	4 338	2 100	6	2	Spinning (Vented)
Deerma Dem V2 Portable Rapid Clothes Dryer 2 Layer 	399	500 – 1 000	11 – 15	0.5 – 3	Heater
Air-O-Dry Portable Electric Clothes Dryer Bag 	299	800	3	1	Blower
SOKANO Portable Electric Cloth Hanger Dryer 	99.90	150	0.3	3	Hot or Cool Air

The Samsung clothes drying product has an acceptable performance with relatively high load weight at 6 kg for a drying time of 3 hours. However, the product consumes the highest amount of power (2 100 W) and it is very expensive (RM4 338) compared to the other products. The SOKANO clothes dryer may cost the least among all the products at RM99.90 but it is limited to drying only one piece of clothes at a time. It takes a very long time (3 hours) to dry only one piece of clothes because of the drying method using hot or cool air.

The Air-O-Dry and Deerma Dem clothes dryer have the best performance with not too much power consumption, relative large load weight and short drying time. The difference between these two products is the method of drying; one product uses a heater while the other uses a blower. However, based on the customer reviews, the Air-O-Dry product has a downside of having loud blower sounds, melting of plastic parts and breaks down after first use. The Deerma Dem product did not have any bad customer reviews in particular.

2.6 Literature Review on Drying Process

The drying process of clothes should be understood, as it is crucial to design an efficient and effective clothes dryer prototype. Heat and mass transfer occurs simultaneously from inner of material, the surface of a material and the surrounding, which makes an energy-intense process (Sousa, Motta Lima and Pereira, 2006). The moisture in the form of water particles travels in a solid body by hydrodynamic motion depending on the moisture content and temperature of the fabric and surrounding. The drying rate of clothes can be observed to analyse its changes from the start when the fabric is damp until it is completely dried. The kinetic behaviour of water particles and the temperature distribution varies according to the pressure and temperature in the drying chamber. The pore structure of fabrics may slow down the drying rate as evaporation of moisture is obstructing.

The moisture content of clothes depends on the relative humidity (RH) of the surroundings and not in control by the temperature. The temperature of the surrounding, however, affects the drying rate and the ability to draw the water particles out of the fabric.

Therefore, the ambient temperature will create different temperature distributions on the surface of the fabric and vary according to the changes in temperature. The drying process is more effective if the air in the drying chamber is replaced with fresh air to reduce moisture in the drying chamber air.

The drying process has three-period stages that begin with warming up period, remain at the evaporation period, and finally, decreasing rate period (Heidner & L. Heidner, 2016). Based on Figure 2.4, the following explains each stage of the process:

(i) Warmup time region will heat dryer and laundry to desired temperature.

(ii) At the evaporation or constant drying stage, the drying rate of laundry depends on the difference of partial vapour pressure of moisture on the surface of laundry. Hence, the drying chamber has to be supplied with sufficient airflow to remove the moisture.

(iii) The decreasing rate stage of drying is comprised of mass transport, fry and cool down region of the graph. The rate will slow down, as the moisture from inside of the fabric will start to evaporate. The moisture from the inner of the fabric will start to dry when the water content from the surface of the fabric has been removed.

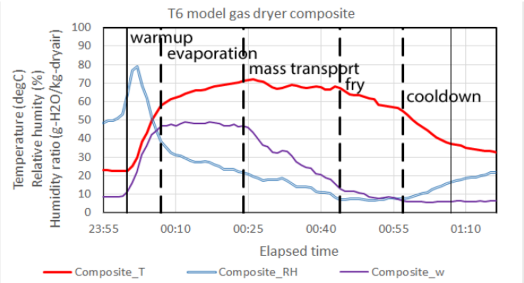


Figure 2.4: Periods of Drying Process (Source: Heidner & L. Heidner, 2016)

Clothes will absorb moisture if it is over-dry because the fabric needs to achieve equilibrium moisture content with surrounding 20 – 25 °C temperature and 50% RH (Heidner & L. Heidner, 2016). The clothes do not necessarily need to be exposed to high heat for a long time; besides it may destroy the fabric. The cotton fabric takes a longer time to dry as it absorbs water to fibre core, unlike synthetic fibres that have tubular structure fibre and do not absorb moisture easily. The clothes dried within the same period depend on the pore and fibre structure of fabric material.

The flow of air varies in the drying chamber because of density difference, pressure gradient and temperature distribution. When the waste heat from the outdoor unit release into the drying chamber, a portion of air within the drying chamber will gain energy to form hot air and the other portion of air may not gain as much energy, which remains as cold air. The air movement from one region to another region also known as wind, which significantly influences the drying rate of clothes. The hot air particles will move and collide frequently so the particles are farther apart and reduce the density of the air. Since the density of hot air is lower than cold air, the hot air will move up and the cold air will fall.

Air pressure also influences the density of the air; higher density of air, higher air pressure. Hot air is less dense so it will have lower pressure and cold air is the inverse of it. Thus, cold air will move in the direction of the hot air. However, if the temperature difference of air is large enough, the hot air will travel to the cold air region. The temperature gradient must be significant enough for the higher temperature to flow towards lower temperature. Temperature affects the air pressure and it changes depending on the surrounding or other heat source. The study of properties is to ensure that all parts of fabrics are dried and more moisture flushes out from the drying chamber.

Figure 2.5 is a simplified version of the Psychometric Chart, which is used to examine several properties of the ambient air during clothes drying. The following are the properties that can be found from the Psychometric Chart:

(i) Dry bulb temperature is the temperature of the air, so it can be taken using a normal thermometer.
(ii) Wet-bulb temperature is the saturation temperature of the air, which is measure using a thermometer with the moist bulb.
(iii) Relative Humidity is the ratio between water vapour fraction in air and saturated wet air fraction for the same pressure and temperature.
(iv) Moisture content (or humidity ratio) is the ratio between the mass of water vapour in wet air and the mass of dry air.
(v) Dew Point Temperature is the temperature of air for wet air to saturate into water vapour.

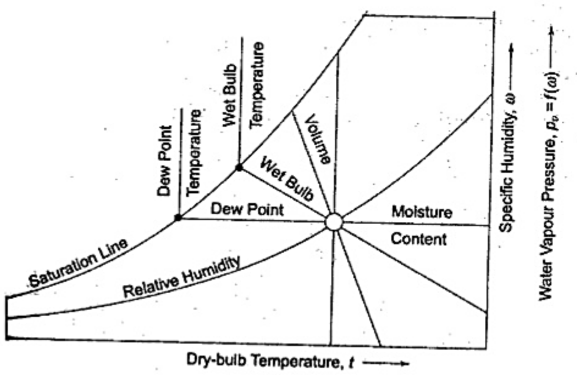


Figure 2.5: Simplified Psychometric Chart (Source: Manoj, 2019)

If at least two properties known by measuring during the experiment, all other properties of air can be derived using the Psychometric chart. The drying rate can be analysed by these properties and observe the properties react to changes of condition.

The relative humidity of air varies with its temperature. Hot air can store more water vapour compared to cold air so air with high temperature will have a lower relative humidity (Condair.co.uk, 2019). Even when both samples of air (One is cold air and the other one is hot air.) has the same amount of moisture, hotter air absorbs more moisture. When the dry-bulb temperature increases and the relative humidity decreases, this condition will reduce the dew-point temperature making it easier to evaporate and condensate. Dew forms as small droplets of water when the moisture of the clothes condensate and larger droplets of water will form as time passes by.

The performance of the heat pump clothes dryer will be evaluated by comparing the drying rate computed from the drying properties and air properties. For the drying properties, the drying rate can be calculated from the mass of clothes and drying time using Formula 2.3. The mass of clothes should be illustrated in a graph so that the equation of the graph can be derived to estimate the drying time of clothes. For the air properties, the drying rate was calculated by plotting the air conditions at the inlet and outlet of the drying chamber on the Psychometric chart. The drying process of the clothes is a complex process that includes evaporation, cooling, humidifying and diffusion of air in the drying chamber. The process was simplified by assuming to be a cooling and humidifying process that has only one inlet and one outlet as shown in Figure 2.6.

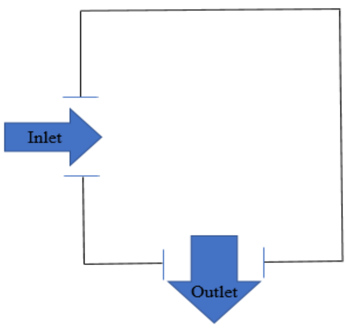


Figure 2.6: The Inlet and Outlet of Drying Chamber from Side View

Dry air mass flow rate, $\dot{m}_a$ for both the inlet and outlet, must be equal and can be calculated using the following formula:

$$\dot{m}_a = \frac{AV}{v} \tag{2.4}$$

where

A = Area of the inlet, m^2

V = Velocity of air at inlet, ms^{-1}

v = Specific volume of air at inlet, m^3/kg

The drying rate, $\dot{m}$ based on air properties then is calculated using the below formula:

$$\dot{m} = \dot{m}_a(\omega_1 - \omega_2) \tag{2.5}$$

where

ω_1 = Specific humidity of air at the inlet

ω_2 = Specific humidity of air at the outlet

The percentage difference between both of the drying rates should be smaller for a better performance as it means that all the heat supplied from the air conditioner was directed in the drying chamber and fully utilized to dry the clothes. The difference would mean that there is a loss in heat and moisture through a different route other than through the inlet and outlet. This is the reason for this evaluation because it will help with the improvement of further studies.

2.7 Summary

In conclusion, it may be summarized that waste heat from an air conditioner is a useful energy source for drying clothes. The clothes dryer should be designed according to the behaviour of the waste heat so the drying rate of clothes is maximized. The performance of the air conditioner is limited when the design of the clothes dryer encloses the outlet of the condenser. The moisture content in the drying drum also must flush out constantly for good performance of clothes dryer. The clothes dryers available in the market are expensive, space-consuming and energy-intensive so this newly designed prototype is a good replacement. This drying process does not have a bad impact on the environment and does not sacrifice the needs of the users.

CHAPTER 3

METHODOLOGY AND WORK PLAN

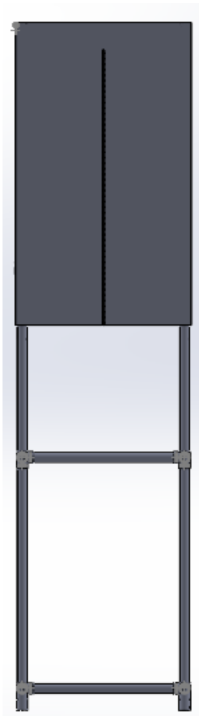
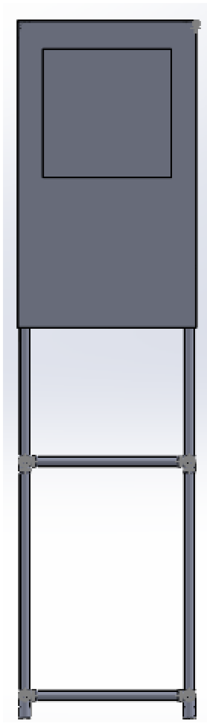
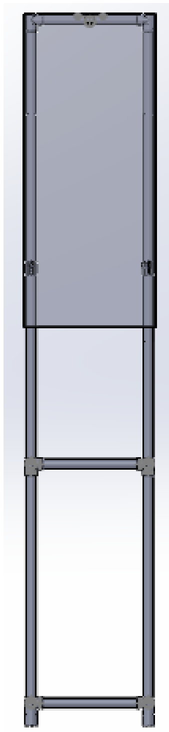
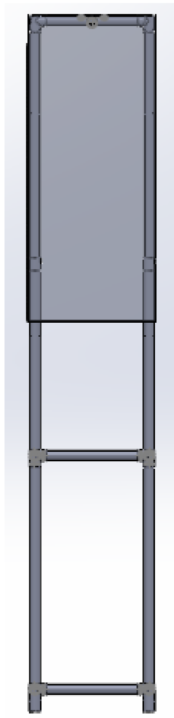
3.1 Introduction

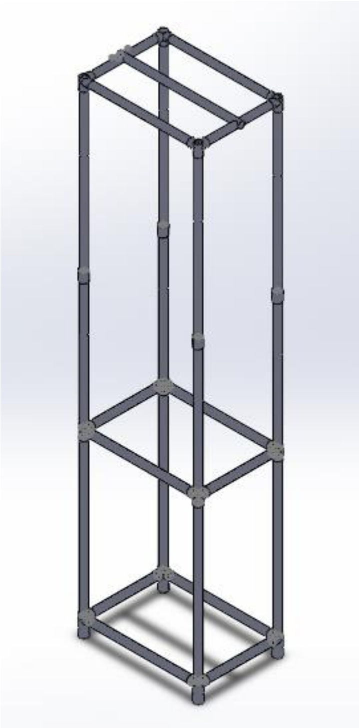
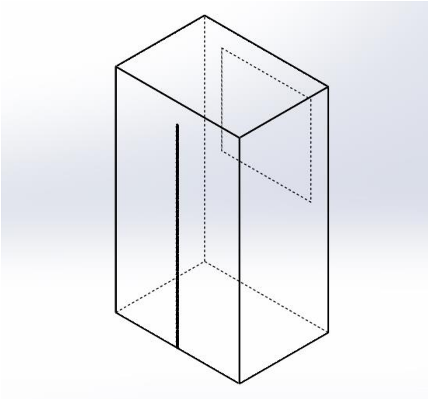
The experiment was created to make sure the performance of the clothes dryer can be fully evaluated. Various criteria were considered to observe and analyse the prototype from a different perspective. The main components required are an air conditioner and the clothes dryer prototype. The prototype was constructed as similar to the final design of the clothes dryer made. In this experiment, a portable air conditioner was used as a replacement of the split unit air conditioner. The portable one has a much smaller cooling load but has the same function so the effect of it was studied.

3.2 Clothes Dryer Prototype

Figure 3.1 shows the SolidWorks drawing of the clothes dryer prototype in a different direction of views.

Figure 3.1: Clothes Dryer Prototype Drawing

Front	Back	Left	Right
			

Frame	Cloth
	

The dimension and a few components for the final design of the clothes dryer were indicated in Figure 3.2.

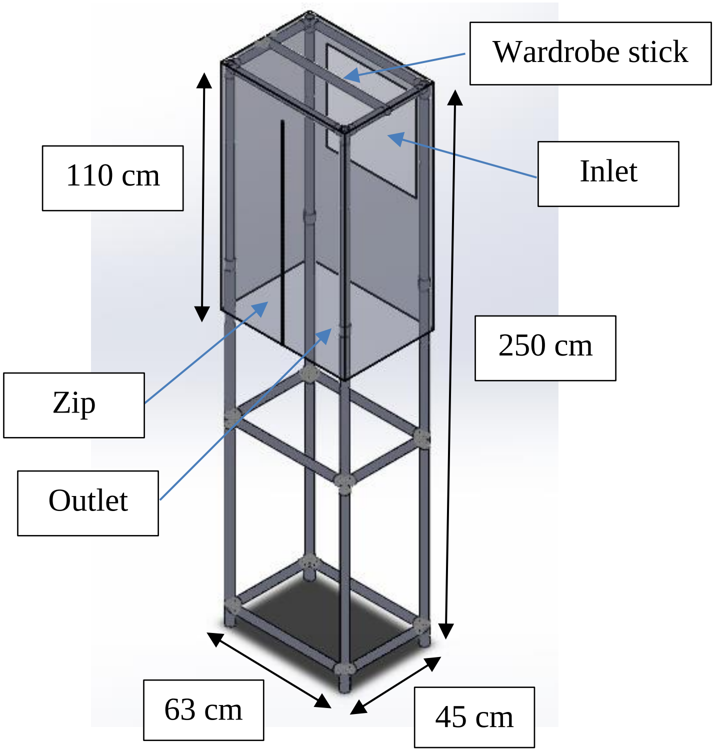


Figure 3.2: Clothes Dryer Prototype in SolidWorks

Figure 3.3 whereas depicts the actual clothes dryer prototype that was used for the experiment in a different direction of views.

Figure 3.3: Actual Clothes Dryer Prototype in Experiment

Front	Back
	
Left	Right
	
Frame	Cloth
	

The dimensions for the actual design of the clothes dryer was indicated in Figure 3.4.

Figure 3.4: Clothes Dryer Prototype Set-Up in Lab

3.3 Characteristics of Final Design

3.3.1 Position of Inlet and Outlet of Drying Chamber

The inlet and outlet were positioned so that waste heat will circulate within the drying chamber to dry the clothes before it leaves. The inlet is placed at the back while the outlet is placed at the bottom in Figure 3.5. If waste heat was supply through the back, heat will follow from left to right (1). After hot air flows in, it will naturally move up due to density difference (2). This cause temperature difference with the surrounding air and draw it into the drying chamber and flush out hot air (3).

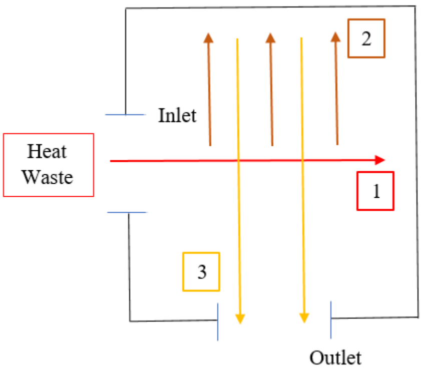


Figure 3.5: Circulation of Hot Air in the Drying Chamber (Side View)

3.3.2 Material of Drying Chamber's Fabric

Heat should retain and circulate in the drying chamber before releasing to the surrounding. The fabric of the drying chamber should be a good insulator to prevent heat loss and light weighted so it is easy to handle. The fabric must have fewer pores so heat does not seep out. Sailcloth with aluminium foil lining was used as the fabric for the drying chamber (Suntivarakorn et al., 2009). However, the prototype suggests using a 100% polyester 4 pass blackout cloth, which is used in curtains. "Pass" refers to the blackout level so 4 pass means that 4 layers of foam were used to retain the heat and maximize drying rate. This is because the foam has a better insulation layer compared to an aluminium foil.

Figure 3.6: 100% Polyester 4 Pass Blackout Fabric

3.3.3 Orientation of Clothes in Drying Chamber

The orientation of clothes affects the surface area exposed to the heat. Based on the left of Figure 3.7, if the clothes are placed in series, hot air is blocked by the first piece of clothes and only a little heat can transfer to the following clothes through the sides or pores of the fabric. The clothes further away from the inlet will dry slower and users may need to rearrange the order of clothes to speed up the drying process. However, if the clothes are placed in parallel, heat can flow in between them as in Figure 3.7 on right. It is easier and faster for each piece of clothes to dry at an equal rate.

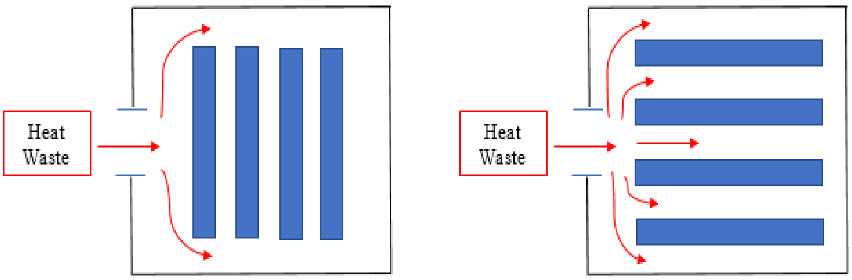


Figure 3.7: Series (Left) and Parallel (Right) Orientation of Clothes from Top View

3.3.4 Other Features of Clothes Dryer

A simple reach stick was design as shown in Figure 3.8 to ease the hanging and removing of clothes. One end is a C-shape to hook the clothes and the other end is a ring shape so it can hang to keep.

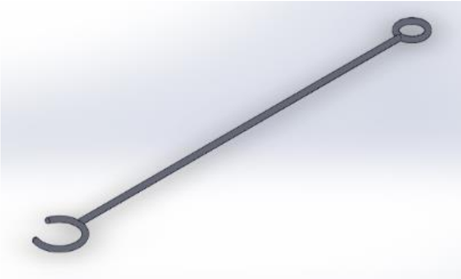


Figure 3.8: Schematic Design of Reach Stick Design

Besides that, the clothes dryer was designed to implement in residential buildings that have a floor-to-floor height of roughly 2.3 m (Bumseok, 2012). The outdoor unit of a split type air conditioner is generally installed at a high height to maximize cooling performance. If the clothes dryer is installed at or above the outlet of the outdoor unit, it is at a height that is difficult to reach by users as Malaysians have an average height of 164.7 cm (Wecare4eyes.com, 2019). Hence, the frame can be lengthened and shorten using a extend pole mechanism.

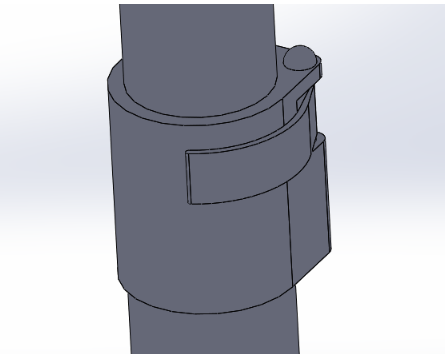


Figure 3.9: Extend Pole Mechanism

3.4 Equipment and Material

The experiment is a test run of clothes dryer prototype, so effectiveness and performance are measured. The following is a list of equipment and materials needed to verify this study:

Table 3.1: List of Equipment and Material of Experiment

Item Description	Quantity
Portable Air Conditioner 1.5 HP	1
Washing Machine	1
Weighing Machine	1
Hygrometer	1
Anemometer	1
Stopwatch	1
Cotton T-shirt	12
Hanger	12
Wood Board	1
Laundry Rack Frame	1
Rack cover cloth	1

The clothes dryer prototype was tested using an apparatus set-up shown in Figure 3.10. The position of equipment and materials is similar to the actual installation of the clothes dryer. Measuring equipment records the mass of clothes and the properties of air at the inlet and outlet of the clothes dryer.

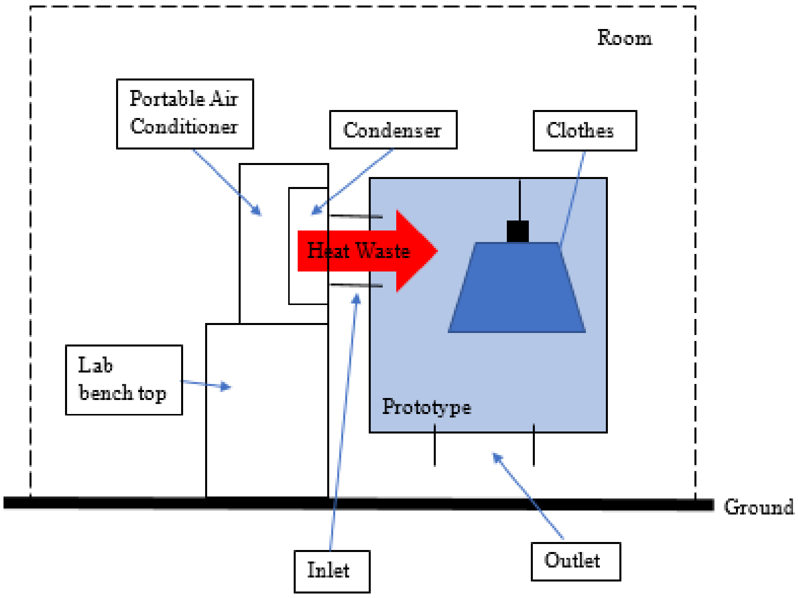


Figure 3.10: Schematic Drawing of Apparatus Set-Up

3.5 Experiment Procedure

The prototype was examined with different variables to verify the performance for various conditions in reality. The procedure was split into four parts to test different variables as stated below.

(i) In Part 1, different drying methods were compared to justify its usage.
(ii) In Part 2, effect of different temperature on drying rate was observed.
(iii) In Part 3, suitable clothes load analysed by a range of several clothes.
(iv) In Part 4, change in drying rate when the inlet is fully sealed and not.

Part 1: Testing Clothes Dryer Prototype with Three Different Drying Methods

(i) Set up the apparatus as shown in Figure 3.10.
(ii) Weigh 1.0 kg of cotton t-shirt.
(iii) Wash and spin-dry the t-shirt using a washing machine. Then, take the weight of the clothes.
(iv) Place the clothes indoors and start the stopwatch.
(v) Record the mass of clothes, airflow speed, temperature and humidity at the inlet, outlet, middle and ambient for 0, 1, 2, 3 and 4 hours.
(vi) Repeat step 1 to 5 with outdoor and waste heat (20 °C) drying method.

Part 2: Testing Clothes Dryer Prototype with Different Temperature Setting

(i) Set up the apparatus as shown in Figure 3.10.
(ii) Weigh 1.0 kg of cotton t-shirt.
(iii) Wash and spin-dry the t-shirt using the washing machine. Then, take the weight of the clothes.
(iv) Switch on the air conditioner and set the temperature to 18 °C.
(v) Place the clothes in the drying chamber and start the stopwatch.
(vi) Record the mass of clothes, airflow speed, temperature and humidity at the inlet, outlet, middle and ambient for 0, 1, 2, 3 and 4 hours.
(vii) Repeat step 1 to 5 with 20 and 22 °C.

Part 3: Testing Clothes Dryer Prototype with Different Clothes Load

(i) Set up the apparatus as shown in Figure 3.10.

(ii) Weigh 6 pieces (0.5 kg) of cotton t-shirt.

(iii) Wash and spin-dry the t-shirt using the washing machine. Then, take the weight of the clothes.

(iv) Switch on the air conditioner and set the temperature to 20 °C.

(v) Place the clothes in the drying chamber and start the stopwatch.

(vi) Record the mass of clothes, airflow speed, temperature and humidity at the inlet, outlet, middle and ambient for 0, 1, 2, 3 and 4 hours.

(vii) Repeat step 1 to 5 with 3 pieces (1.0 kg), 9 pieces (1.5 kg) and 12 pieces (2.5 kg) of cotton clothes.

Part 4: Testing Clothes Dryer Prototype with Sealed and Unsealed Inlet

(i) Set up the apparatus as shown in Figure 3.10.

(ii) Weigh 1.0 kg of cotton t-shirt.

(iii) Wash and spin-dry the t-shirt using the washing machine. Then, take the weight of the clothes.

(iv) Switch on the air conditioner and set the temperature to 20 °C.

(v) Place the clothes in the drying chamber and start the stopwatch.

(vi) Record the mass of clothes, airflow speed, temperature and humidity at the inlet, outlet, middle and ambient for 0, 1, 2, 3 and 4 hours.

(vii) Repeat step 1 to 5 with the wooden board removed.

3.6 Summary

This experiment replicates the actual usage process of the heat pump clothes dryer. The prototype was tested in various components to assess the performance of the clothes dryer. This experiment should be able to prove the performance of heat pump clothes dryer using a portable clothes dryer. The different drying methods (i.e. indoor, outdoor, waste heat) were compared to justify its usage. The manner that the drying rate is affected was observed when the change in temperature setting (i.e. 18 ºC, 20 ºC, 22 ºC). It analyses the suitable clothes load of this clothes dryer design by using a range of several clothes (i.e. 3, 6, 9, and 12 pieces). This experiment helps verify if the portable air conditioner will give the desired outcome as a clothes dryer.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Effect of Different Drying Method

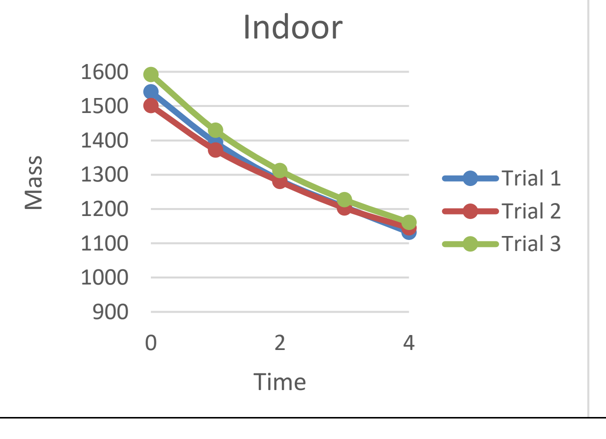
The properties of the drying process were tabulated to analyse the drying rate and moisture removed within 4 hours for different drying method as shown in Table 4.1.

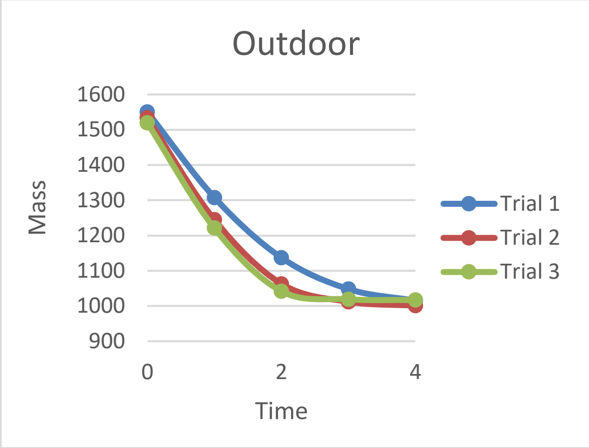
Table 4.1: The Drying Properties for Different Clothes Load

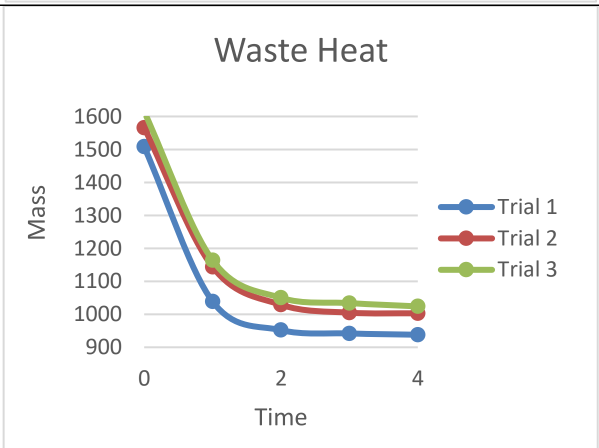
Method	Trial	Initial mass (g)	After spin dry (g)	Moisture added (g)	Time taken to dry (hr)	Drying rate (kg/hr)	Moisture removed in 4 hrs (g)
Indoor	1	981	1541	560	5.169	0.108	409
	2	991	1501	510	5.024	0.102	356
	3	992	1592	600	6.639	0.090	431
Outdoor	1	988	1551	563	4.809	0.117	536
	2	989	1534	545	4.182	0.130	533
	3	993	1520	527	4.215	0.125	503
Waste Heat	1	969	1508	539	1.547	0.348	570
	2	1051	1602	551	1.515	0.364	584
	3	1051	1615	564	1.974	0.286	591

The change of mass in clothes over a period of 4 hours was plotted for different drying method and tabulated in Figure 4.1.

Figure 4.1: Graph of Mass of Clothes against Time for Different Drying Methods







The conventional methods of drying indoor and outdoor were different from a new method of drying using waste heat of a portable air conditioner. The outdoor method is commonly utilized, and it took approximately 4 hours for a small clothes load of 1 kg. The experiment for the outdoor method was carried out at the balcony of a condominium and not on the porch of a landed house. The drying rate is much slower as there is less sunlight and wind exposure when clothes are sunned at the balcony. If the clothes are not dried quickly enough, moss will form and create a musty smell and so, more users are shifting to a clothes dryer. The indoor method is not an alternative as the drying time is very long at 5 to 6.5 hours.

Based on Figure 4.1, the graphs showed that the waste heat method has the steepest gradient and it represents the drying rate. The waste heat method has the highest drying rate of ~0.364 kg/hr in comparison to the indoor (0.108 kg/hr) and outdoor (0.130 kg/hr) method. Substantially shorter drying time was taken using the waste heat of the portable air conditioner. This is because all methods rely on a different source of heat and airflow.

The waste heat method relies on the waste heat of the portable air conditioner and the airflow of the exhaust fan while the outdoor method relies on the heat of sunlight and airflow from the wind. The outdoor drying rate fluctuates depending on the weather but the waste heat method will not fluctuate as much because the air conditioner can still absorb heat from occupants, appliances and lights.

The drying process occurs due to the temperature and moisture difference between the clothes and air. The waste heat method provides an air source with a much higher temperature and lowers moisture content compared to the atmospheric temperature. The drying process slows down and comes to stop when the air and clothes become equilibrium. So, if the air is hotter and drier, more moisture will be extracted from the clothes. The amount of moisture extracted from the clothes after 4 hours for waste heat method is more than the moisture added to the clothes, unlike the other two methods as seen in Table 4.1. The clothes will be heated by the end of the 4 hours as it conducts heat from the waste heat of the portable air conditioner and ensures the clothes is dried.

4.2 Effect of Change in Temperature Setting

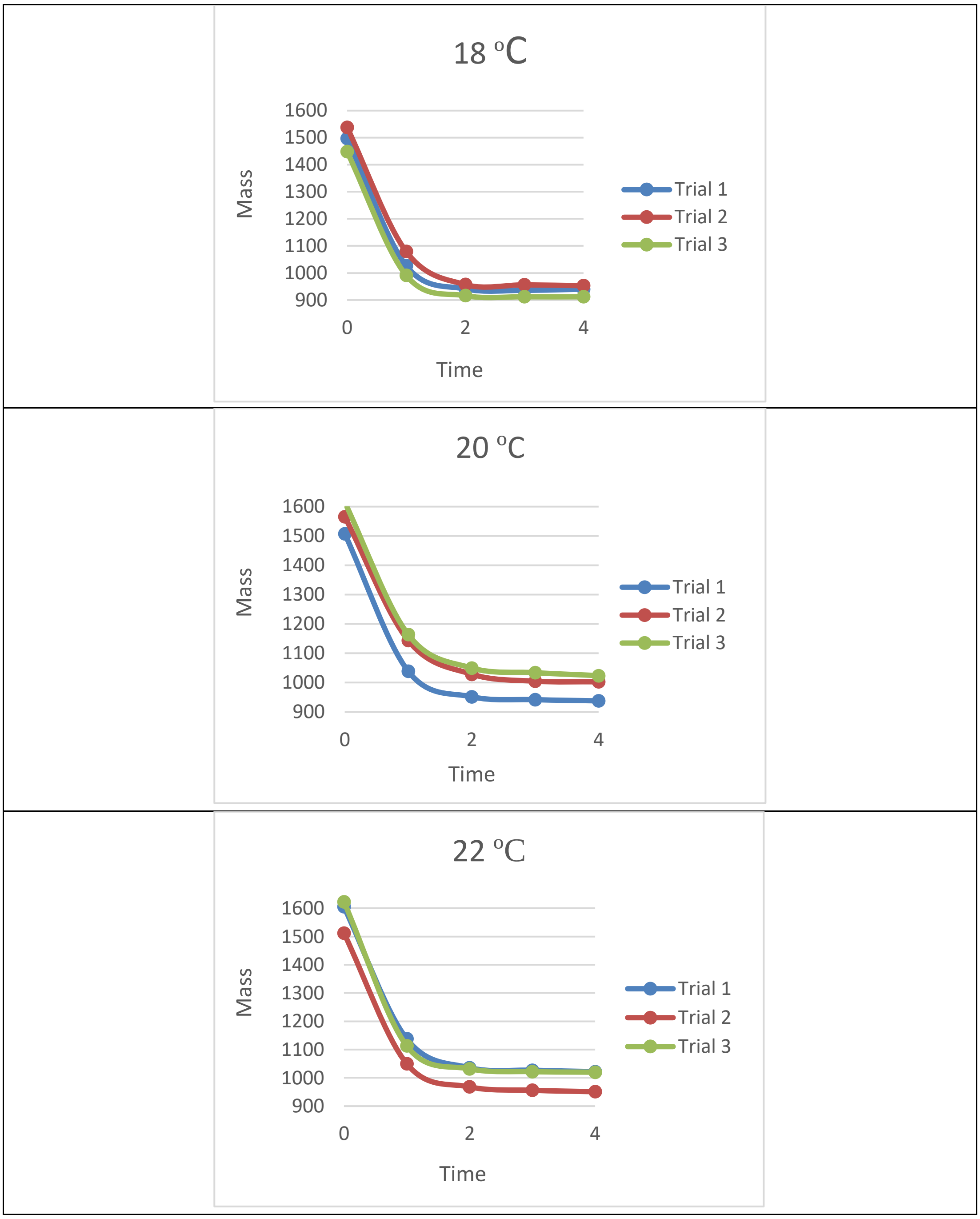
The properties of the drying process were measured and recorded to evaluate the drying rate and the moisture removed within 4 hours for different temperature setting as displayed in Table 4.2.

Table 4.2: The Drying Properties for Different Temperature Setting

Setting (ºC)	Trial	Initial mass (g)	After spin dry (g)	Moisture added (g)	Average moisture added (g)	Time taken to dry (hr)	Drying rate (kg/hr)	Average drying rate (kg/hr)	Moisture removed in 4 hrs (g)	Average moisture removed in 4 hrs (g)
18	1	972	1497	525	531.3	1.366	0.3844	0.3633	557	559.3
	2	982	1538	556		1.592	0.3492		585	
	3	935	1448	513		1.439	0.3564		536	
20	1	969	1508	539	551.3	1.547	0.3484	0.3326	570	581.7
	2	1051	1602	551		1.515	0.3637		584	
	3	1051	1615	564		1.974	0.2856		591	
22	1	1052	1605	553	557.7	1.636	0.3380	0.3338	583	582.3
	2	976	1512	536		1.698	0.3157		561	
	3	1039	1623	584		1.680	0.3477		603	

The change of mass in clothes over a period of 4 hours was plotted for different temperature setting and tabulated in Figure 4.2.

Figure 4.2: Graph of Mass of Clothes against Time for Different Temperature Setting



The portable air conditioner has several temperature settings. This part of the experiment analyses the drying rate when there is a change in temperature setting by 2 °C.

When the temperature setting is lower, more heat will be extracted from the room and clothes should dry faster. The heat removed from the room flows through the portable air conditioner and goes into the inlet of the clothes dryer chamber. Thus, the amount of heat removed from the room is equal to the amount of heat supplied to the clothes dryer. Based on the results in Table 4.2, increasing temperature by 2 ºC does not have much effect on the drying rate as the drying time is roughly 1.5 hours. The amount of heat extracted from the room is approximately the same for all temperature settings. For a portable air conditioner, there is not much difference in drying rate for different temperature setting.

As the temperature setting rises from 18 to 22 ºC, the average drying rate declines from 0.3633 to 0.3338 kg/hr. When the temperature setting lowers, more heat has to be removed from the room to lower its temperature. The heat supplied to the clothes dryer increases as the heat extracted from the room increases. So, the clothes dry faster when more heat supplied to the drying chamber. This trend proves that more waste heat was supplied and moisture is extracted at a faster rate when the temperature setting is lower.

As discussed previously, when the temperature setting is higher, the drying rate should slow down. However, the average drying rate for temperature setting of 22 ºC (0.3338 kg/hr) went against the trend and incline upwards from for temperature setting of 20 ºC (0.3326 kg/hr). This is because the highest inlet temperature is 39.11 ºC temperature setting of 22 ºC in TableB-3 while it is only 36.38 ºC for temperature setting of 20 ºC in TableB-2. The hotter air supplied to the drying chamber causes a higher drying rate.

As the temperature setting increases, the average amount of moisture removed after 4 hours increases. The moisture removed in 4 hours does not depend on the temperature setting but depends on the amount of moisture added. Since the effect of change in temperature setting is not significant, more readings have to be taken to analyse rather than an hourly reading to observe if the fluctuation of temperature and relative humidity is the reason for the trend of moisture removed in 4 hours.

4.3 Effect of Increasing Clothes Load

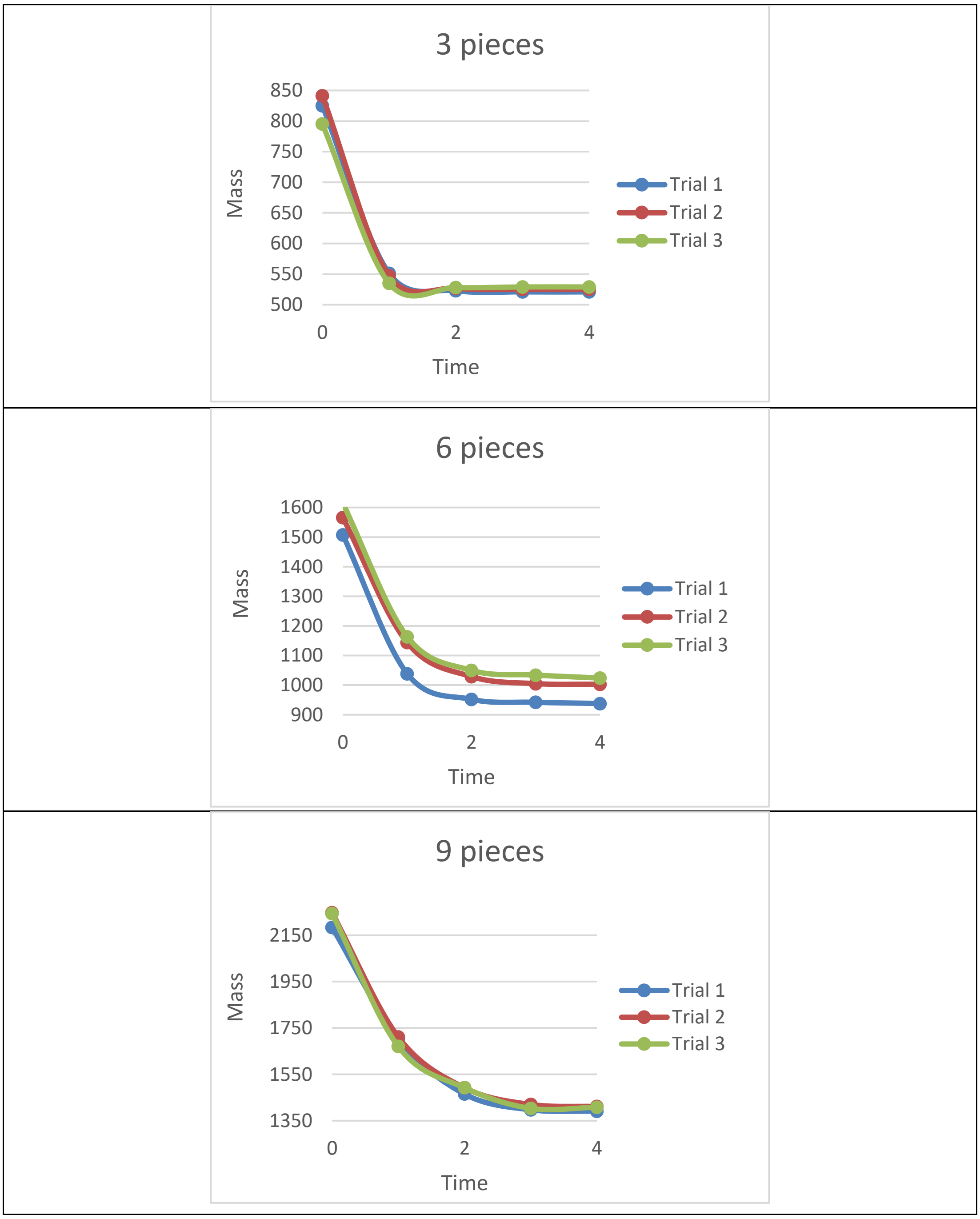
The properties of the drying process evaluate the drying rate and the moisture removed within 4 hours for different clothes load as displayed in Table 4.3. The drying time for trial 1 of 12 pieces of clothes could not be estimated due to the lack of points on the graph.

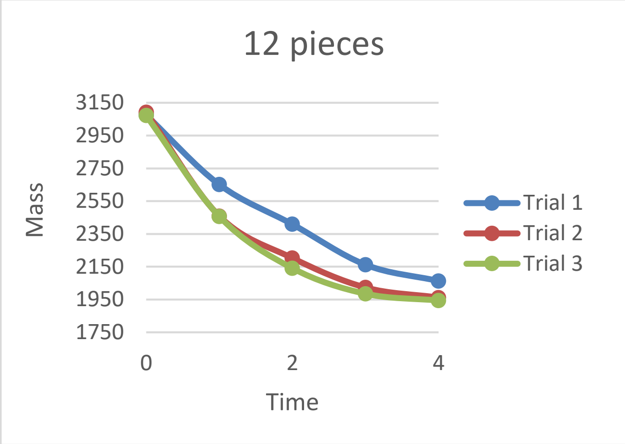
Table 4.3: The Drying Properties for Different Clothes Load

Number of clothes	Trial	Initial mass (g)	After spin dry (g)	Moisture added (g)	Time taken to dry (hr)	Drying rate (kg/hr)	Average drying rate (kg/hr)	Moisture removed in 4 hrs (g)	Average moisture removed in 4 hrs (g)	Average Moisture removed per shirt (g)
3	1	533	825	292	1.248	0.2341	0.2544	304	295.3	98.4
	2	535	841	306	1.158	0.2642		316		
	3	537	795	258	0.974	0.2650		266		
6	1	969	1508	539	1.547	0.3484	0.3326	570	574.7	95.8
	2	1051	1602	551	1.515	0.3637		563		
	3	1051	1615	564	1.974	0.2856		591		
9	1	1439	2184	745	2.217	0.3360	0.3157	793	821.7	91.3
	2	1438	2247	809	2.608	0.3102		836		
	3	1424	2244	820	2.724	0.3010		836		
12	1	2006	3075	1069	-	-	0.3406	1012	1090.0	90.8
	2	1972	3092	1120	3.383	0.3310		1130		
	3	1972	3072	1100	3.142	0.3501		1128		

The change of mass in clothes over a period of 4 hours was plotted for different clothes load and tabulated in Figure 4.3.

Figure 4.3: Graph of Mass of Clothes against Time for Different Clothes Load





Based on the results above in Table 4.3, as the number of clothes increases from 3 to 12 pieces (~ 0.5 – 2 kg), the time to dry increases from roughly 1 to 3 hours. However, the drying rate rises when the load gets heavier. Larger clothes load would mean that there is a larger surface area of clothes exposed to the heat. Moisture absorbs heat and gains energy to evaporate. So, there is more moisture drawn out of the clothes at one time making the average drying rate grow from 0.2544 to 0.3406 kg/hr.

When the number of clothes increases from 3 to 12 pieces, the average amount of moisture removed after 4 hours increases from 295.3 to 1090.0 g as shown in Table 4.3. When there are more clothes, there is more fabric to hold moisture. There is more moisture available to evaporate during the drying process.

The amount of moisture removed for each shirt does depend on the structure of fabric but also the heat absorbed by each shirt. The average moisture removed per shirt reduces from 98.4 to 90.8 g as the clothes load is bigger. The heat supplied by the portable air conditioner is roughly the same due to the cooling load. So, when there are more clothes, each piece of the shirt will absorb less heat.

This part of the experiment determines the clothes load that will dry by a specific period. Since our prototype relies on the waste heat of the portable air conditioner, this study have a limited time of heat supply to dry the clothes. Assuming that users will use their air conditioner for about 3 hours, the amount of clothes that they can dry at one time is about 1.5 kg according to Table 4.5. One person has about 8 kg of laundry per week so they need to use about four to five times.

4.4 Difference of Sealed and Unsealed Inlet

The properties of the drying process were measured and recorded to evaluate the drying rate for a sealed and unsealed inlet as displayed in Table 4.4.

Table 4.4: The Drying Properties for Sealed and Unsealed Inlet

Inlet	Initial mass (g)	After spin dry (g)	Moisture added (g)	Time taken to dry (hr)	Drying rate (kg/hr)
Sealed	1439	2184	745	2.217	0.3360
Unsealed	1458	2276	818	3.287	0.2488

The change of mass in clothes over a period of 4 hours was plotted for a sealed and unsealed inlet as shown in Figure 4.4.

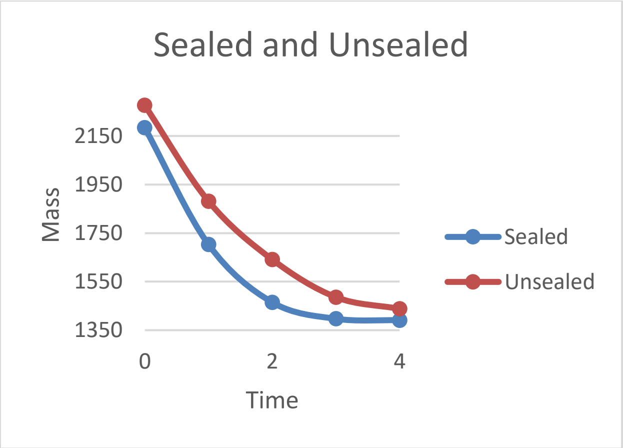


Figure 4.4: Graph of Mass of Clothes against Time for a Sealed and Unsealed Inlet

Sealed means the open end with a piece of wood (Left of Figure 4.6) and unsealed means just the open end (Right of Figure 4.6). While the experiment was carried out, it was observed that the unsealed inlet takes a longer time compared to the sealed inlet. The clothes on the open end are damper in relative to the close end of the drying chamber because the heat is lost and not fully supplied to the drying chamber. The close end becomes sealed when the heat is supplied. It creates a high-pressure region in the drying chamber and presses the cloth against the back of the air conditioner to seal the portion of the inlet. The open end does not have a surface to seal the inlet so a piece of wood was placed.

Figure 4.5: Side View of Closed End at Inlet

a) b)

Figure 4.6: Side View of Opened End at Inlet. a) Sealed and b) Unsealed

After sealed, the drying rate increases from 0.249 kg/ hr to 0.336 kg/hr. All the waste heat extracted will be fully directed into the drying chamber with minimal loss. A simple alteration at inlet makes the clothes dry significantly faster with almost an hour difference. So, a feature of placing a Velcro tape at the open end of the inlet was added to make sure it is sealed.

4.5 Effect of Ambient Conditions

The atmospheric conditions of a room are uncontrollable and do not fluctuate only because of the weather but also because of waste heat from appliances, people and lights. This means even on rainy days, the waste heat extracted may still be the same as a sunny day. The drying rate depends on the conditions of the airflow from the outlet of the portable air conditioner. If the airflow from the air conditioner has a higher temperature and lower relative humidity, then clothes will have a higher drying rate.

The effect of room ambient temperature can be explained clearly using Trial 1 of 12 pieces of clothes in Table 4.3 as an example. Based on the inlet air properties in FigureC-4, the temperature for all three trials varies about 34.5 ºC but the relative humidity for Trial 2 and 3 fluctuates about 45 % while Trial 1 fluctuates about 65%. This means that the inlet airflow for Trial 1 was moister and moisture gradient between the air and clothes is smaller. The drying time for Trial 1 will be much longer as proven in the experiment; taking more than 4 hours to dry. The inlet airflow should be hotter and drier for higher drying rate.

4.6 Analysis of Moisture Extraction

For all experiments, the graphs illustrate the same concave up decreasing shape as shown in Figure 4.1, 4.2 and 4.3. The only difference between the graphs is the gradient of the curve, which is the drying rate. The moisture extracted per hour over the period of 4 hours is different and becomes less as the time pass. The evaporation of moisture from clothes is due to the moisture gradient between the clothes and air as it tries to bring them to equilibrium conditions. As time pass by, the clothes become drier and the moisture gradient is smaller so the drying rate becomes slower.

Drying rate is most significant at the start when the moisture gradient is at the steepest so the amount of moisture extracted for the first hour is always the highest. Hence, it is important to take advantage of this condition to maximize the drying rate. If the initial moisture gradient is small, the drying time will be much longer. The drying process is a cooling and humidifying process as depicted in Figure 4.7. Point 1 represents the air at the inlet and point 2 is at the outlet. The air becomes cooler and wetter once exiting the drying chamber.

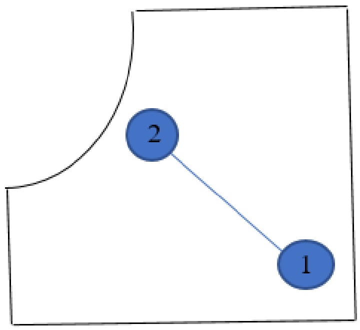


Figure 4.7: The Drying Process Plotted in Psychometric Chart

4.7 Evaluate the Performance of Prototype

Based on properties of air at the inlet and outlet, the amount of moisture extracted from the clothes for each hour was estimated using Formula 2.5 and it was tabulated in TableB-5, TableB-6, TableB-7, TableC-6, TableC-7, TableC-8 and TableC-9. The value was then compared with the experimental amount of moisture removed per hour and obtained the percentage difference of it. In the calculation, this study assumed that there are one inlet and one outlet in this drying process. So, this part test how efficient the heat from inlet air was utilized and check if heat seeps out through any other holes.

The percentage difference has a very wide range with an accurate result of 0.41 % (Trial 2 of 22 ºC temperature setting) and an imprecise result of 410.73 % (Trial 2 of 12 pieces). Most of the results have a high percentage difference of more than 80%, which means that the results are not accurate and there are other outlets for air to exit the drying chamber. Based on the calculation, the mass flow rate of dry air at the inlet and outlet is not equal that means it is leaving through other parts of the drying chamber. The air is leaving through cloth pores, sewing gap or zip. The moisture could be absorbed by the cloth because it is a 4 layered foam cloth.

The average percentage difference grows slowly from 59.86 % to 99.26 % over the 4 hours of the experiment as exhibits in Table 4.5. This means that the results become more inaccurate and less precise as time passes. When the drying chamber holds more heat, the pores of blackout curtain cloth will expand because of its foamed like insulation layer. So, heat and moisture can escape from the drying chamber and reduce the correctness of the comparison.

Table 4.5: Average Percentage Difference of Results

	Time (hr)				Maximum	Minimum
	1	2	3	4		
Average Percentage difference (%)	59.86	88.66	92.37	99.26	410.73	0.41

4.8 Evaluate the Costing of Prototype

The product cost consists of direct and indirect cost, which is material cost, labour cost, tooling cost, and other costs. The price of the product was estimated based on the actual price of materials purchased for the prototype and a profit margin was added. A relatively high-profit margin of 50 % was added to cover the other costs that were not included in the estimated price. Since the calculated product cost is RM200.7 in Table 4.6, so this study set the selling price to RM210.

Table 4.6: Cost of Clothes Dryer

Item	Unit	Cost per unit	Price
Palazzo – 100% Polyester 4 Pass Blackout Fabric	3	34.8	104.4
Clothes Wardrobe	1	23.5	23.5
Reaching stick	1	5.9	5.9
Total material cost			133.8
Profit Margin			66.9
Product cost			200.7

4.9 Comparison with Commercial Clothes Dryer

The clothes dryer was differentiated to acquire the advantages and disadvantages of the different heat source (Heater and Waste Heat). A commercial clothes dryer uses a heater in general but the prototype uses waste heat. Several important specifications were considered and compared in Table 4.7. An indicator column was added, where Green is favourable to waste heat clothes dryer and Red is unfavourable.

7 out of 12 components sides the waste heat clothes dryer making it more favourable. The main components that are highly considered by most users are cost, size, load weight and drying time. The size of the heater clothes dryer is smaller and will consume less space if it is a combo machine (Washer + Dryer). Also, the heater clothes dryer takes a larger load and dry in a shorter time. This makes the heater clothes dryer a better choice but the cost of it and the cost of running it is very high. In our experiment, the waste heat source was from a portable air conditioner so the heat supplied is much less compared to a split unit air conditioner. If a larger heat source was used, the drying rate and load weight will be higher and the waste heat clothes dryer will have a better potential to compete in the market.

Table 4.7: Comparison of Specification for Heater and Waste Heat Clothes Dryer

	Heater	Waste Heat	Indicator
Price (RM)	4 338	210	
Dimension (mm)	600 x 850 x 600	630 x 2500 x 450	
Power Consumption (W)	2 100	0	
Specific Mass Extraction Rate (SMER) (kg/kWh)	0.680	∞	
Weight of appliance (kg)	81	3	
Load Weight (kg)	6	1.5	
Drying Rate (kg/hr)	1.429	0.350	
Portability	No	Yes	
Maintenance	Yes	No	
Moving parts	Yes	No	
Weather sensitive	No	Yes	
Combo machine	Washer and dryer	Dryer only	

Besides that, the ergonomic criteria for waste heat pump clothes dryer are important. The clothes dryer design is made up of several metal bars, corner joints and drying chamber cloth. The prototype used in the experiment has a similar frame but shorter and without the extend pole mechanism. The design is easy to assemble and disassemble to build and keep away since the parts are simple and the constructing procedure is easy. The corner joints and metal bars have to be connected according to the manual but do not require any equipment. Aside from that, the design should not leave behind any footprint since users will not want to leave any damage to their property.

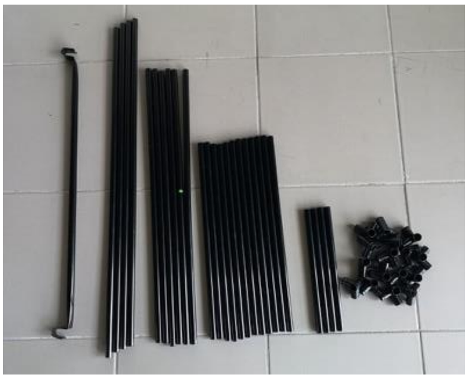


Figure 4.8: The Parts of Frame for Experiment Prototype

4.10 Summary

The results demonstrate the abilities of the heat pump clothes dryer prototype through the testing in the experiment. The portable air conditioner has a smaller waste heat than a split unit air conditioner but the performance is sufficient enough to exhibit a better drying rate than indoor and outdoor drying methods. The drying rate does not fluctuate much when the temperature setting was changed by 2 ºC. Also, the prototype can dry up to 1.5 kg of clothes within 3 hours when the inlet is completely sealed. This study observed that the ambient temperature of air affects the drying rate of clothes as it depends on the weather as well as the heat from the occupants, lights, and appliances. The drying chamber cloth is not a perfect boundary because results show that heat and moisture may have seeped out through sewing gap, zip and cloth pores. The heat pump clothes dryer design has many positive traits over the commercial clothes drier and most of all, the price of the product is very affordable.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The first objective was achieved in the Literature Review. The heat accumulated from sunny weather, occupants, appliances and lights generates a discomforting and hot room. The heat pump clothes dryer is the most suitable type of dryer because the waste heat is used and no extra heat is produced. Besides, it does not consume electricity so it reduces environmental impact and creates sustainability. The Psychometric Chart and computation were suitable methods to interpret the physics of air and the drying process.

The next objective was fulfilled through the formulation of the Methodology. This study developed a simple, cheap, light and eco-friendly clothes dryer which applies the principles of a heat pump clothes dryer. Various elements and features were selected carefully to maximize the performance of clothes dryer and user's convenience. The experimental process helps complete the third objective of the study. The final design of the heat pump clothes dryer was modified to fabricate a simple prototype, so it can link with the portable air conditioner. This experiment uses existing products so a substitute rather than manufacturing from scratch.

The results of the experiment were analysed to achieve the last objective. The results prove that users will get a faster drying rate with a heat pump clothes dryer even if the heat source is from a portable clothes dryer. The waste heat method has the highest drying rate of ~0.364 kg/hr compared to the indoor and outdoor method. Even though there is not much effect when changing the temperature setting, the average drying rate declines from 0.3633 to 0.3338 kg/hr when the temperature setting rises from 18 to 22 ºC. It takes roughly 1 to 3 hours to dry about 0.5 to 2 kg of clothes. Also, clothes dry faster in a dry condition (45 %) than when in a moist condition (65 %). The average percentage difference increasing from 59.86 % to 99.26 % over the 4 hours of the experiment, which means that the prototype exhibits a declining performance. The prototype has an important advantage of a very low estimated product cost of RM210.

5.2 Recommendations for Future Work

During the experiment, there were several possible sources of errors and cause of percentage difference in calculated and experimental results. The inlet and outlet reading is not tally and maybe a few seconds differences as it is not taken simultaneously. The mass of clothes, temperature, relative humidity and airflow speed should be monitored more closely rather than hourly. The air properties at different locations of the drying chamber also should be measured. It is hard to trace the reason for lower or higher drying rate and do not know the fluctuating trend of conditions through the process. The drying chamber is open every hour for measurement so heat and moisture are released and may affect the reading.

A data logger with sensors can be used to measure and record the properties of air and the mass of clothes over time. The sensors measure the air properties and mass of clothes and then recorded by the data logger. The inlet and outlet airflow reading is simultaneous and many readings are taken so trend and fluctuation of properties are clearer. The sensors can be placed at different parts of the drying chamber and allow not to open the chamber. The temperature gradient of the drying chamber can be observed by using an infrared camera. Besides that, a part of the experiment that tests the lifespan of the prototype should be added as it determines the frequency of replacing the product.

Furthermore, the heat pump clothes dryer prototype using the 100 % Polyester 4 Pass Blackout cloth should be tested with a split unit air conditioner so that the results can be compared with previous researches that use sailcloth and aluminium foil lining. The decision of using a blackout curtain cloth is because it was assumed that the complex insulating surface will trap more heat in the drying chamber to speed up the drying rate. The drying rates could not be compared to the previous researches because a portable air conditioner was used.

REFERENCES

Ambarita, H., Nasution, D., Gunawan, S. and Nasution, A. (2017). Performance and Characteristics of Heat Pump Clothes Drier. *IOP Conference Series: Materials Science and Engineering*, 180, p.012027.

Ambarita, H., Nasution, A., Siahaan, N. and Kawai, H. (2016). Performance of a clothes drying cabinet by utilizing waste heat from a split-type residential air conditioner. *Case Studies in Thermal Engineering*, 8, pp.105-114.

Beko.co.uk. (2019). *Benefits of a Heat Pump Tumble Dryer Infographic*. [online] Available at: https://www.beko.co.uk/lifestyle/benefits-of-a-tumble-dryer-heat-pump [Accessed 21 Jul. 2019].

Bumseok Chun. (2012). Two- and Three-Dimensional Urban Core Determinants of the Urban Heat Island: A Statistical Approach. *Journal of Environmental Science and Engineering*, [online] (ISSN 1934-8932), pp.363-378. Available at: http://works.bepress.com/bumseok_chun/7/ [Accessed 12 Aug. 2019].

Climatetechwiki.org. (2019). *Solar dryer*. [online] Available at: https://www.climatetechwiki.org/technology/jiqweb-edf [Accessed 21 Jul. 2019].

Condair.co.uk. (2019). *Textile manufacturing*. [online] Available at: https://www.condair.co.uk/knowledge-hub/the-importance-of-humidity-control-in-textile-processing [Accessed 29 Jul. 2019].

Fix My Blinds. (2019). *Clutch System Diagrams for Roller Shades*. [online] Available at: https://www.fixmyblinds.com/v/vspfiles/ins-roller-clutch.html [Accessed 15 Aug. 2019].

Heidner, Amy & L. Heidner, Dennis. (2016). A field study of the residential clothes drying process. 1-8. 10.1109/SusTech.2016.7897134.

John, C. (2010). *Waste heat vs greenhouse warming*. [online] Skeptical Science.com. Available at: https://skepticalscience.com/print.php?n=288 [Accessed 21 Jul. 2019].

Lazada.com.my. (2019). *Air-O-Dry Portable Electric Clothes Dryer Bag (Blue)*. [online] Available at: https://www.lazada.com.my/products/air-o-dry-portable-electric-clothes-dryer-bag-blue-i126464726-s139555345.html?spm=a2o4k.searchlist.list.1.2c135fa6R2sG9Z&search=1 [Accessed 14 Aug. 2019].

Lazada.com.my. (2019). *Deerma Dem V2 Portable Rapid Clothes Dryer 2 Layer - Navy Blue*. [online] Available at: https://www.lazada.com.my/products/deerma-dem-v2-portable-rapid-clothes-dryer-2-layer-navy-blue-i352804139-s498743659.html?spm=a2o4k.searchlist.list.5.69a76a94H4WKMX&search=1 [Accessed 14 Aug. 2019].

Lazada.com.my. (2019). *Samsung Front Load Washer Inverter QuickDrive, 9KG Washer & 6KG Dryer: WD90N64FOOW/FQ*. [online] Available at: https://www.lazada.com.my/products/samsung-front-load-inverter-quickdrive-eco-bubble-tech-9kg-washer-6kg-dryer-wd90n64foowfq-free-backpack-worth-rm129-i330062443-s458754638.html?spm=a2o4k.searchlist.list.5.1c9e77ee6HtgOc&search=1 [Accessed 14 Aug. 2019].

Lazada.com.my. (2019). *SOKANO Professional Portable Electric Cloth Dryer Hanger Dryer (Hot Air and Cool Air Duo Mode)*. [online] Available at: https://www.lazada.com.my/products/sokano-professional-portable-electric-cloth-dryer-hanger-dryer-hot-air-and-cool-air-duo-mode-i303598112-s405871635.html?spm=a2o4k.searchlist.list.1.3c822640QmiXAi&search=1s480705664.html?laz_trackid=2:mm_150020493_51201078_2010201090:clk5hhoka1dd3h6blpli90 [Accessed 14 Aug. 2019].

Made-in-China.com. (2019). *100% Polyester 600d Twill PVC Foam Coating Fabric for Bags&Luggage*. [online] Available at: https://sinyotextile.en.made-in-china.com/product/eSdQDtKjbRpn/China-100-Polyester-600d-Twill-PVC-Foam-Coating-Fabric-for-Bags-Luggage.html [Accessed 14 Aug. 2019].

Made-in-China.com. (2019). *High Density Oxford Nylon Twill Fabric with Waterproof for Backpacks*. [online] Available at: https://sinyotextile.en.made-in-china.com/product/JKvnSINxhPpX/China-High-Density-Oxford-Nylon-Twill-Fabric-with-Waterproof-for-Backpacks.html [Accessed 14 Aug. 2019].

Mahlia, T M Indra & C. G, Hor & Masjuki, H.H. & M, Husnawan & Varman, Mahendra & Mekhilef, Saad. (2010). Clothes Drying from Room Air Conditioning Waste Heat: Thermodynamics Investigation. *Arabian Journal for Science and Engineering*. 35. 339-351.

Manoj, P. (2015). *Psychrometric Chart*. [online] Available at: https://image.slidesharecdn.com/2-150214032338-conversion-gate01/95/2-psychrometric-chart-1-638.jpg?cb=1423905939 [Accessed 24 Jul. 2019].

Peng, C., Ravi, S., Patel, V., Momen, A. and Moghaddam, S. (2017). Physics of direct-contact ultrasonic cloth drying process. *Energy*, 125, pp.498-508.

Scied.ucar.edu. (2019). *The Highs and Lows of Air Pressure*. [online] Available at: https://scied.ucar.edu/shortcontent/highs-and-lows-air-pressure [Accessed 25 Jul. 2019].

Science ABC. (2016). *AC Working Principle: How Does An Air Conditioner (AC) Work*?. [online] Available at: https://www.scienceabc.com/innovation/air-conditioner-ac-work.html [Accessed 21 Jul. 2019].

Shen, Bo; Gluesenkamp, Kyle; Bansal, Pradeep; and Beers, David, "Heat Pump Clothes Dryer Model Development" (2016). *International Refrigeration and Air Conditioning Conference*. Paper 1755.

Shopee.com.my. (2019). *3M Command Medium Picture Hanging White Strips (4 Sets) 17201*. [online] Available at: https://shopee.com.my/3M-Command-Medium-Picture-Hanging-White-Strips--4-Sets--17201-i.41985388.1598194823?gclid=EAIaIQobChMIpt_OteGK5AIVFR4rCh1bDAyQEAQYAiABEgL_pvD_BwE [Accessed 14 Aug. 2019].

Sousa, L., Motta Lima, O. and Pereira, N. (2006). Analysis of Drying Kinetics and Moisture Distribution in Convective Textile Fabric Drying. *Drying Technology*, 24(4), pp.485-497.

Suntivarakorn, P., Satmarong, S., Benjapiyaporn, Chatchai & Theerakulpisut, S. (2009). An Experimental Study on Clothes Drying Using Waste Heat from Split Type Air Conditioner. *World Academy of Science, Engineering and Technology International Journal of Mechanical and Mechatronics Engineering*, 3(5), pp.483 - 488.

Ultrasonic Technology Solutions. (2019). *Ultrasonic drying*. [online] Available at: https://www.ultratechsol.com/what-is-ultrasonic-drying.html [Accessed 22 Jul. 2019].

Wecare4eyes.com. (2019). *Chart showing the average height of males and females in various world countries*. [online] Available at: http://www.wecare4eyes.com/averageemployeeheights.htm [Accessed 12 Aug. 2019].

Yourhome.gov.au. (2019). *Orientation*. [online] Available at: http://www.yourhome.gov.au/passive-design/orientation [Accessed 21 Jul. 2019].

APPENDICES

APPENDIX A: Results for Different Drying Methods

TableA-1: Mass Properties for Different Drying Methods

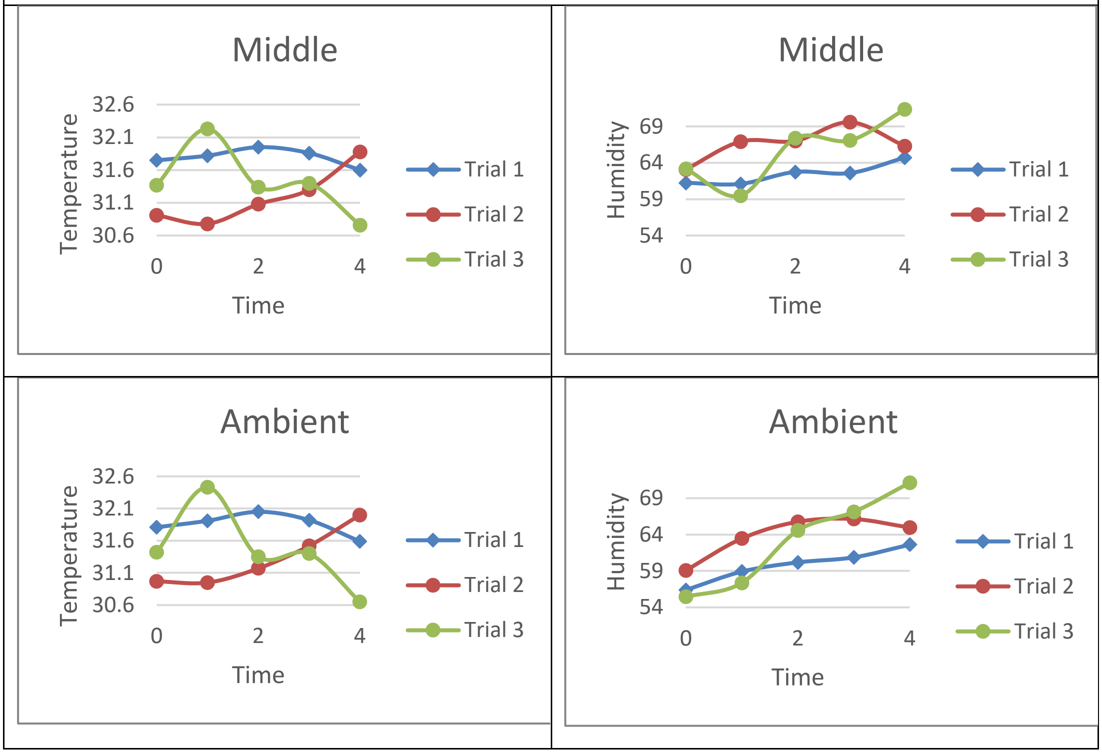
Method	Trial	Time	Mass of Clothes (g)							Moisture Added (g)	Time to dry (hr)	Drying Rate (kg/hr)	Moisture removed in 4 hours (g)	Note
			Dry	Spin Dry	After Drying									
					0	1	2	3	4					
Indoor	1	14:34	981	1541	1541	1394	1284	1206	1132	560	5.169	0.108	409	Wet
	2	14:52	991	1501	1501	1372	1280	1203	1145	510	5.024	0.102	356	Wet
	3	13:57	992	1592	1592	1429	1312	1227	1161	600	6.639	0.090	431	Wet
Outdoor	1	14:43	988	1551	1551	1308	1137	1048	1015	563	4.809	0.117	536	Damp
	2	15:05	989	1534	1534	1245	1063	1012	1001	545	4.182	0.130	533	Damp
	3	14:13	993	1520	1520	1221	1042	1019	1017	527	4.215	0.125	503	Damp
Waste Heat	1	12:48	969	1508	1508	1039	952	942	938	539	1.547	0.348	570	Dry
	2	13:12	1051	1602	1602	1126	1027	1017	1018	551	1.515	0.364	584	Dry
	3	8:35	1051	1615	1615	1164	1050	1034	1024	564	1.974	0.286	591	Dry

TableA-2: Drying Properties for Different Drying Method (Indoor and Outdoor)

			Indoor					Outdoor				
			Time (hr)					Time (hr)				
Position	Properties	Trial	0	1	2	3	4	0	1	2	3	4
Middle	Temperature (ºC)	1	31.75	31.82	31.95	31.86	31.6	31.93	32.08	32.06	32.04	31.39
		2	30.91	30.78	31.08	31.3	31.88	31.41	31.12	31.36	31.45	31.34
		3	31.37	32.23	31.34	31.4	30.76	31.04	30.91	31.05	30.26	29.49
	Relative humidity (%)	1	61.25	61.1	62.75	62.59	64.72	58.22	56.52	56.94	52.08	61.34
		2	63.08	66.91	67	69.58	66.3	56.94	62.19	62.27	63.69	62.29
		3	63.15	59.49	67.37	67.08	71.33	63.81	61.26	62.29	64.9	71.91
Ambient	Temperature (ºC)	1	31.81	31.91	32.05	31.92	31.59	31.96	32.12	32.12	32	31.46
		2	30.97	30.95	31.17	31.52	32	31.36	31.12	31.36	31.38	31.35
		3	31.42	32.43	31.35	31.4	30.65	31.08	30.86	31.1	30.26	29.51
	Relative humidity (%)	1	56.38	58.91	60.18	60.87	62.61	54.27	53.98	54.84	52.01	60.87
		2	59.07	63.45	65.76	66.14	64.97	56.49	58.5	60.91	63.59	61.87
		3	55.45	57.36	64.56	67.12	71.12	61.06	58.54	61.64	64.15	71.78

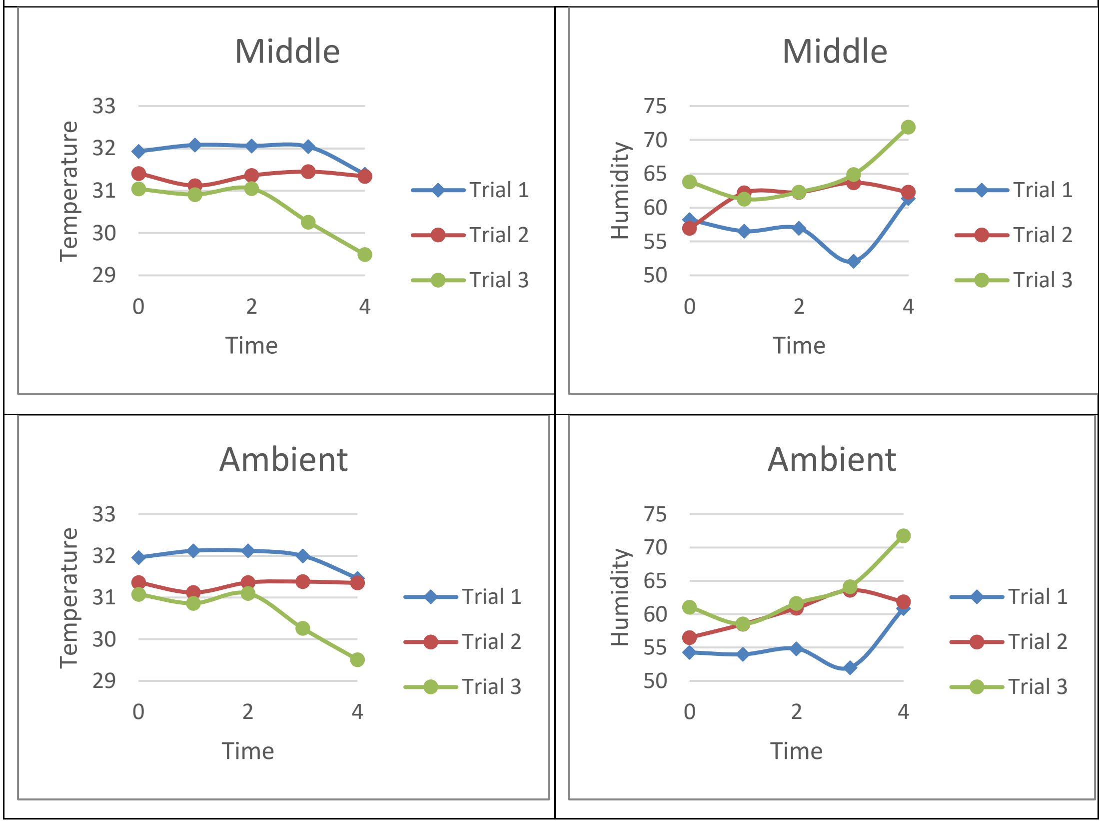
FigureA-1: Graphs of Drying Properties for Indoor Method

Indoor



FigureA-2: Graphs of Drying Properties for Outdoor Method

Outdoor

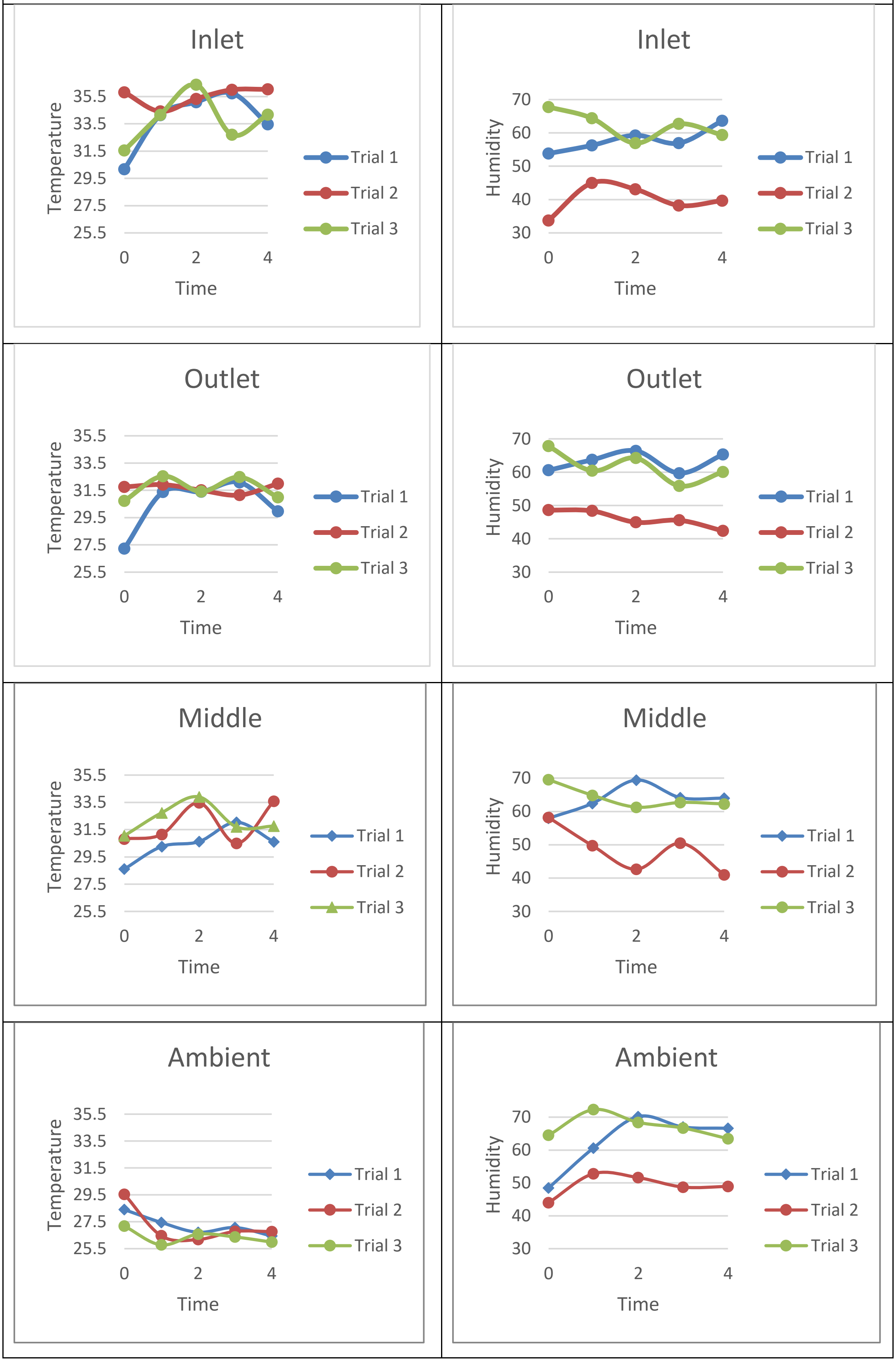


TableA-3: Drying Properties for Waste Heat Method

			Waste Heat				
			Time (hr)				
Position	Properties	Trial	0	1	2	3	4
Inlet	Temperature (ºC)	1	30.18	34.14	35.09	35.75	33.47
		2	35.82	34.41	35.34	36.00	36.03
		3	31.55	34.16	36.38	32.70	34.18
	Relative humidity (%)	1	53.82	56.27	59.29	56.93	63.64
		2	33.74	44.99	43.11	38.25	39.68
		3	67.80	64.40	56.93	62.72	59.38
Outlet	Temperature (ºC)	1	27.23	31.37	31.40	32.09	29.96
		2	31.75	31.92	31.51	31.15	31.99
		3	30.73	32.54	31.41	32.47	30.99
	Relative humidity (%)	1	60.57	63.71	66.42	59.71	65.31
		2	48.63	48.38	44.96	45.56	42.39
		3	67.82	60.45	64.26	55.88	60.09
Middle	Temperature (ºC)	1	28.61	30.26	30.62	32.04	30.61
		2	30.82	31.15	33.47	30.49	33.59
		3	31.05	32.74	33.90	31.70	31.76
	Relative humidity (%)	1	57.95	62.42	69.43	64.16	63.98
		2	58.20	49.74	42.65	50.49	41.00
		3	69.53	64.86	61.29	62.70	62.25
Ambient	Temperature (ºC)	1	28.40	27.45	26.72	27.07	26.44
		2	29.55	26.46	26.18	26.78	26.77
		3	27.18	25.78	26.58	26.37	25.99
	Relative humidity (%)	1	48.45	60.61	70.19	67.00	66.62
		2	43.96	52.80	51.60	48.73	48.93
		3	64.48	72.29	68.40	66.69	63.45

FigureA-3: Graphs of Drying Properties for Waste Heat Method

Waste Heat



APPENDIX B: Results for Different Temperature Setting of Air Conditioner

TableB-1: Mass Properties for Different Temperature Setting

Setting (ºC)	Trial	Time	Mass of Clothes (g)							Moisture Added (g)	Time to dry (hr)	Drying Rate (kg/hr)	Moisture removed in 4 hours (g)
			Dry	Spin Dry	After Drying								
					0	1	2	3	4				
18	1	13:15	972	1497	1497	1027	941	936	940	525	1.366	0.3844	557
	2	13:13	982	1538	1538	1079	957	956	953	556	1.592	0.3492	585
	3	13:17	935	1448	1448	991	916	912	912	513	1.439	0.3564	536
20	1	12:48	969	1508	1508	1039	952	942	938	539	1.547	0.3484	570
	2	13:12	1051	1602	1602	1126	1027	1017	1018	551	1.515	0.3637	584
	3	8:35	1051	1615	1615	1164	1050	1034	1024	564	1.974	0.2856	591
22	1	13:14	1052	1605	1605	1138	1036	1027	1022	553	1.636	0.3380	583
	2	13:28	976	1512	1512	1050	968	956	951	536	1.698	0.3157	561
	3	10:33	1039	1623	1623	1113	1032	1022	1020	584	1.680	0.3477	603

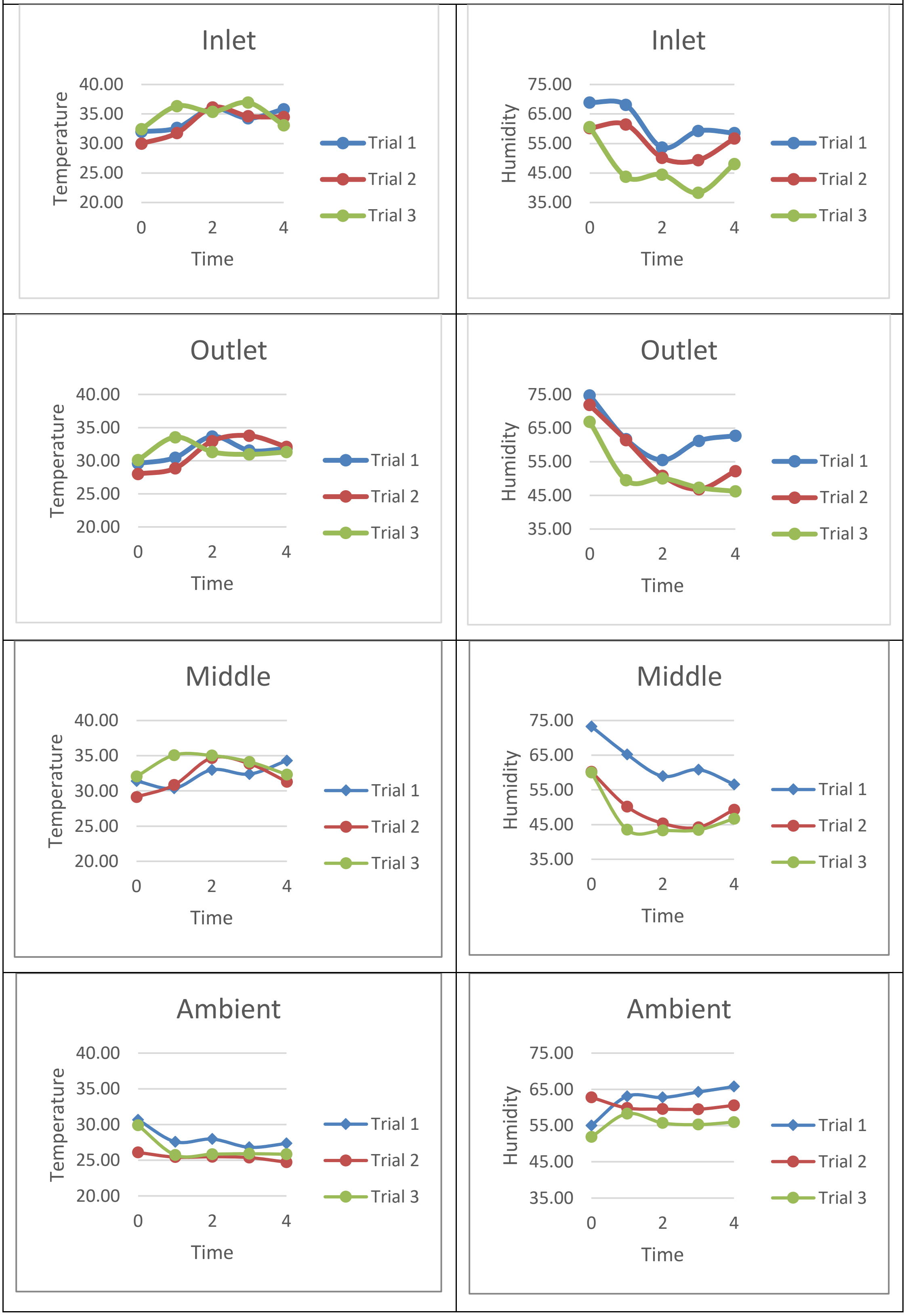
TableB-2: Drying Properties for 18 ºC Temperature Setting

			18 ºC				
			Time (hr)				
Position	Properties	Trial	0	1	2	3	4
Inlet	Temperature (ºC)	1	31.99	32.64	35.96	34.28	35.82
		2	29.99	31.77	36.11	34.64	34.48
		3	32.45	36.34	35.37	36.93	33.11
	Relative humidity (%)	1	68.93	68.08	53.66	59.24	58.55
		2	60.23	61.44	50.17	49.38	56.68
		3	60.54	43.71	44.49	38.28	48.06
	Fan speed (m/s)	1	7.0	5.3	6.5	5.7	5.2
		2	5.8	6.1	5.7	5.4	5.6
		3	5.8	5.0	6.8	4.6	6.0
	Specific volume (m^3/kg)	1	0.894	0.896	0.904	0.9	0.906
		2	0.881	0.889	0.903	0.896	0.899
		3	0.892	0.9	0.897	0.9	0.889
	Mass flowrate (kg/s)	1	0.201	0.152	0.184	0.162	0.147
		2	0.169	0.176	0.162	0.154	0.160
		3	0.167	0.142	0.194	0.131	0.173
	Specific humidity	1	0.0208	0.0213	0.0202	0.0203	0.0219
		2	0.0161	0.0182	0.0190	0.0172	0.0196
		3	0.0187	0.0167	0.0161	0.0151	0.0153
Outlet	Temperature (ºC)	1	29.58	30.47	33.66	31.54	31.83
		2	28.00	28.85	32.97	33.77	32.09
		3	30.11	33.55	31.33	30.96	31.30
	Relative humidity (%)	1	74.75	61.72	55.52	61.22	62.74
		2	71.81	61.43	50.83	46.86	52.21
		3	66.89	49.52	50.09	47.30	46.22
	Fan speed (m/s)	1	0.0	0.0	0.0	1.0	1.9
		2	1.3	1.3	2.5	0.0	0.0
		3	1.3	1.4	1.3	0.0	0.0
	Specific volume (m^3/kg)	1	0.885	0.884	0.895	0.888	0.89
		2	0.877	0.877	0.89	0.891	0.887
		3	0.884	0.892	0.883	0.88	0.881
	Mass flowrate (kg/s)	1	0.000	0.000	0.000	0.319	0.605
		2	0.420	0.420	0.796	0.000	0.000
		3	0.417	0.445	0.417	0.000	0.000

	Specific humidity	1	0.0196	0.0170	0.0183	0.0179	0.0187
		2	0.0171	0.0154	0.0161	0.0155	0.0157
		3	0.0181	0.0162	0.0144	0.0133	0.0133
Middle	Temperature (ºC)	1	31.41	30.37	33.00	32.39	34.31
		2	29.14	30.84	34.68	33.87	31.31
		3	32.06	35.09	35.03	34.14	32.33
	Relative humidity (%)	1	73.32	65.23	58.95	60.84	56.63
		2	60.26	50.19	45.36	44.23	49.31
		3	60.00	43.53	43.32	43.46	46.71
Ambient	Temperature (ºC)	1	30.66	27.59	27.96	26.81	27.34
		2	26.09	25.43	25.49	25.37	24.73
		3	29.89	25.73	25.85	25.91	25.84
	Relative humidity (%)	1	54.98	63.07	62.75	64.26	65.76
		2	62.80	59.86	59.55	59.51	60.58
		3	51.87	58.28	55.71	55.27	55.96

FigureB-1: Graphs of Drying Properties for 18 ºC Temperature Setting

18 ºC



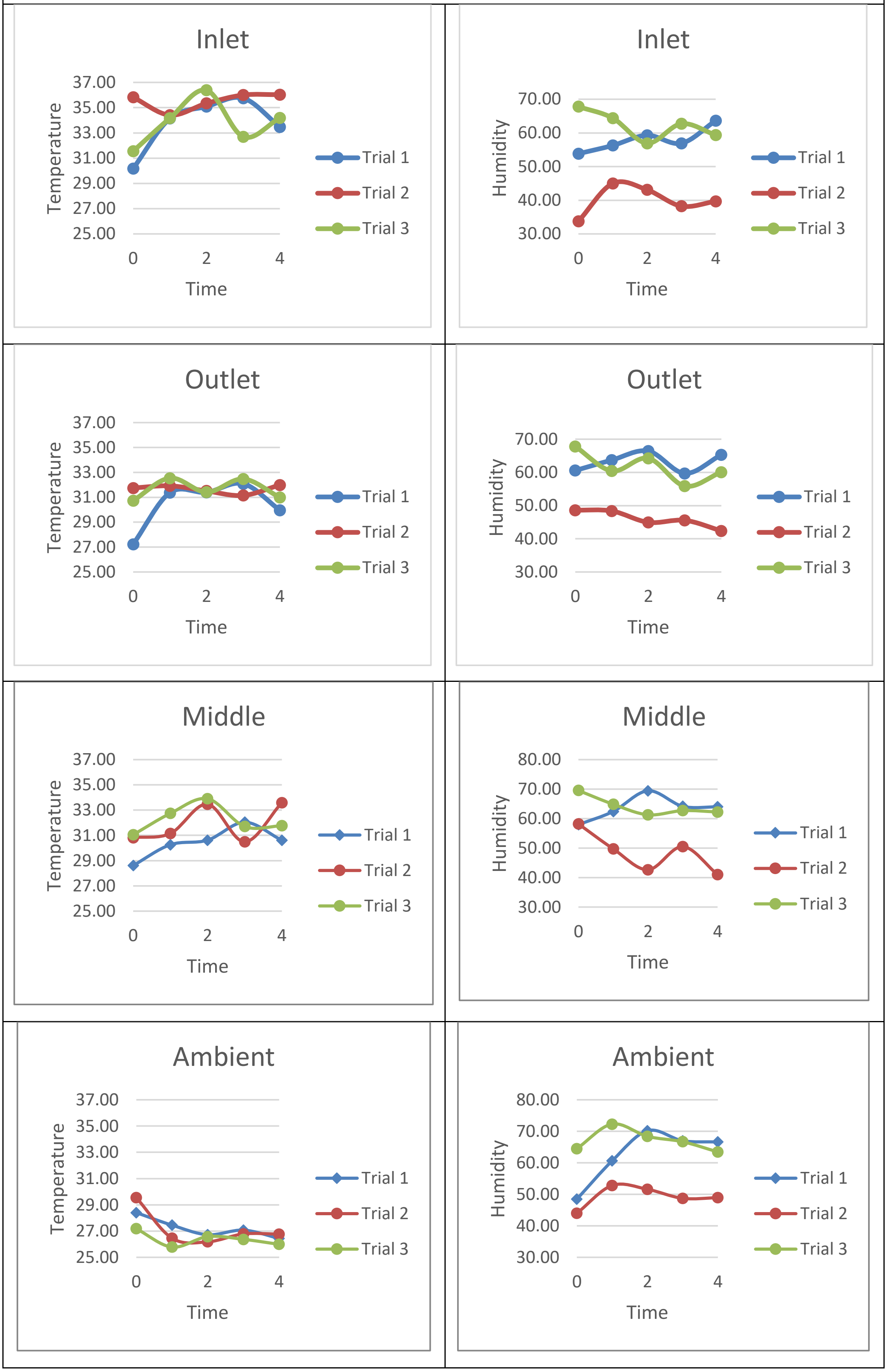
TableB-3: Drying Properties for 20 ºC Temperature Setting

			20 ºC				
			Time (hr)				
Position	Properties	Tria	0	1	2	3	4
Inlet	Temperature (ºC)	1	30.18	34.14	35.09	35.75	33.47
		2	35.82	34.41	35.34	36.00	36.03
		3	31.55	34.16	36.38	32.70	34.18
	Relative humidity (%)	1	53.82	56.27	59.29	56.93	63.64
		2	33.74	44.99	43.11	38.25	39.68
		3	67.80	64.40	56.93	62.72	59.38
	Fan speed (m/s)	1	6.3	5.7	7.1	7.0	6.5
		2	7.4	6.8	6.8	7.7	7.7
		3	6.0	8.2	6.4	5.8	5.7
	Specific volume (m^3/kg)	1	0.88	0.897	0.903	0.905	0.898
		2	0.893	0.893	0.896	0.896	0.897
		3	0.891	0.902	0.908	0.894	0.899
	Mass flowrate (kg/s)	1	0.183	0.163	0.201	0.198	0.185
		2	0.212	0.195	0.194	0.220	0.220
		3	0.173	0.233	0.181	0.166	0.162
	Specific humidity	1	0.014	0.019	0.0213	0.021	0.020
		2	0.012	0.015	0.0156	0.014	0.014
		3	0.019	0.022	0.0220	0.019	0.020
Outlet	Temperature (ºC)	1	27.23	31.37	31.40	32.09	29.96
		2	31.75	31.92	31.51	31.15	31.99
		3	30.73	32.54	31.41	32.47	30.99
	Relative humidity (%)	1	60.57	63.71	66.42	59.71	65.31
		2	48.63	48.38	44.96	45.56	42.39
		3	67.82	60.45	64.26	55.88	60.09
	Fan speed (m/s)	1	0.4	0.4	0.0	0.0	1.0
		2	1.0	1.1	0.8	0.0	1.0
		3	1.6	1.5	1.0	0.0	0.0
	Specific volume (m^3/kg)	1	0.87	0.888	0.89	0.89	0.883
		2	0.884	0.884	0.881	0.88	0.882
		3	0.887	0.892	0.889	0.89	0.885
	Mass flowrate (kg/s)	1	0.130	0.128	0.000	0.000	0.321
		2	0.321	0.353	0.257	0.000	0.000
		3	0.511	0.477	0.319	0.000	0.000

	Specific humidity	1	0.013	0.018	0.0193	0.018	0.017
		2	0.014	0.014	0.0130	0.012	0.012
		3	0.019	0.018	0.0187	0.017	0.017
Middle	Temperature (ºC)	1	28.61	30.26	30.62	32.04	30.61
		2	30.82	31.15	33.47	30.49	33.59
		3	31.05	32.74	33.90	31.70	31.76
	Relative humidity (%)	1	57.95	62.42	69.43	64.16	63.98
		2	58.20	49.74	42.65	50.49	41.00
		3	69.53	64.86	61.29	62.70	62.25
Ambient	Temperature (ºC)	1	28.40	27.45	26.72	27.07	26.44
		2	29.55	26.46	26.18	26.78	26.77
		3	27.18	25.78	26.58	26.37	25.99
	Relative humidity (%)	1	48.45	60.61	70.19	67.00	66.62
		2	43.96	52.80	51.60	48.73	48.93
		3	64.48	72.29	68.40	66.69	63.45

FigureB-2: Graphs of Drying Properties for 20 ºC Temperature Setting

20 ºC



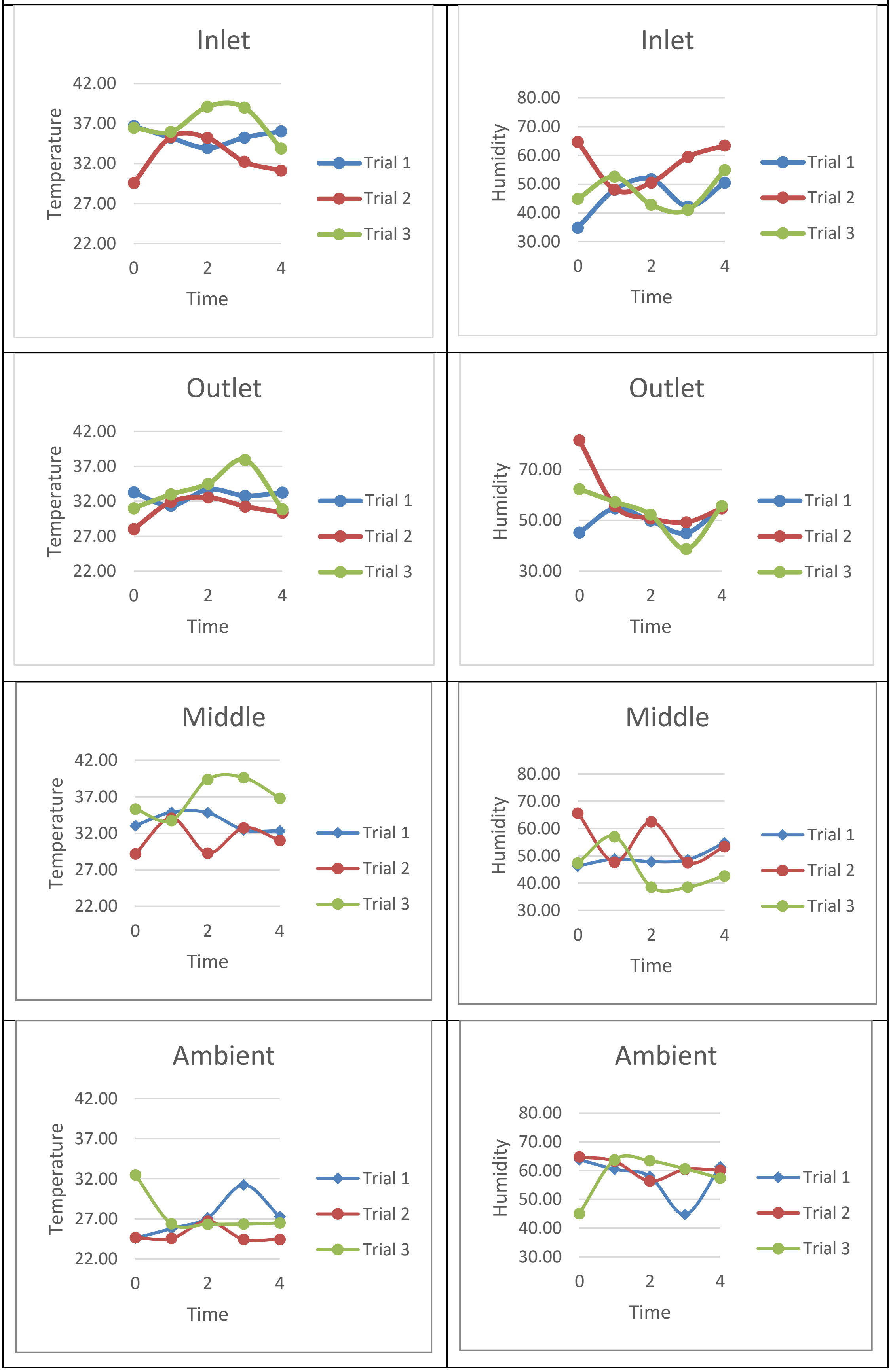
TableB-4: Drying Properties for 22 ºC Temperature Setting

Position	Properties	Trial	22 ºC Time (hr) 0	1	2	3	4
Inlet	Temperature (ºC)	1	36.68	35.24	33.95	35.25	36.02
		2	29.57	35.29	35.20	32.23	31.14
		3	36.47	35.96	39.11	39.00	33.87
	Relative humidity (%)	1	34.79	48.03	51.74	42.23	50.51
		2	64.68	48.11	50.54	59.49	63.46
		3	44.88	52.58	42.82	41.10	54.91
	Fan speed (m/s)	1	7.1	6.7	6.5	6.5	6.5
		2	5.6	5.6	5.0	7.0	5.0
		3	5.6	5.3	6.3	6.5	5.7
	Specific volume (m^3/kg)	1	0.897	0.898	0.894	0.895	0.903
		2	0.881	0.898	0.899	0.89	0.887
		3	0.902	0.904	0.912	0.91	0.896
	Mass flowrate (kg/s)	1	0.203	0.191	0.186	0.186	0.184
		2	0.163	0.160	0.142	0.202	0.144
		3	0.159	0.150	0.177	0.183	0.163
	Specific humidity	1	0.0135	0.0173	0.0173	0.0152	0.0190
		2	0.0169	0.0174	0.0182	0.0181	0.0182
		3	0.0173	0.0198	0.0191	0.0182	0.0183
Outlet	Temperature (ºC)	1	33.29	31.35	33.71	32.79	33.25
		2	28.03	31.91	32.56	31.27	30.38
		3	31.02	32.99	34.52	37.93	30.87
	Relative humidity (%)	1	45.15	54.75	49.83	45.03	55.50
		2	81.57	55.65	50.80	49.27	54.73
		3	62.32	57.20	52.25	38.75	55.70
	Fan speed (m/s)	1	0.0	0.0	1.4	0.0	0.0
		2	0.8	0.4	0.4	0.0	0.0
		3	0.8	0.0	0.8	2.0	0.0
	Specific volume (m^3/kg)	1	0.889	0.885	0.892	0.886	0.893
		2	0.88	0.887	0.888	0.882	0.881
		3	0.886	0.893	0.897	0.904	0.883
	Mass flowrate (kg/s)	1	0.000	0.000	0.445	0.000	0.000
		2	0.258	0.128	0.128	0.000	0.000
		3	0.256	0.000	0.253	0.627	0.000

	Specific humidity	1	0.0145	0.0158	0.0164	0.0141	0.0179
		2	0.0196	0.0166	0.0157	0.0141	0.0149
		3	0.0177	0.0182	0.0181	0.0161	0.0156
Middle	Temperature (ºC)	1	33.06	34.89	34.84	32.47	32.34
		2	29.19	34.09	29.28	32.75	31.02
		3	35.33	33.77	39.38	39.64	36.83
	Relative humidity (%)	1	46.29	48.80	47.83	48.59	54.78
		2	65.68	47.69	62.54	47.54	53.36
		3	47.35	57.06	38.52	38.52	42.67
Ambient	Temperature (ºC)	1	24.59	25.78	27.12	31.24	27.26
		2	24.66	24.54	26.70	24.43	24.44
		3	32.50	26.39	26.32	26.35	26.48
	Relative humidity (%)	1	63.80	60.47	57.97	44.81	61.31
		2	64.74	63.25	56.37	60.43	60.09
		3	45.07	63.73	63.41	60.65	57.36

FigureB-3: Graphs of Drying Properties for 22 ºC Temperature Setting

22 ºC



TableB-5: Moisture Properties for 18 ºC Temperature Setting

	Trial	18 ºC Time (hr) 0	1	2	3	4
Rate of Moisture Remove (kg/s)	1	2.41E-04	6.52E-04	3.50E-04	3.89E-04	4.71E-04
	2	-1.69E-	4.92E-04	4.69E-04	2.62E-04	6.22E-04
	3	1.00E-04	7.12E-05	3.30E-04	2.36E-04	3.46E-04
Theoretical Moisture removed (g)	1	0.0	2345.9	1260.0	1401.9	1694.0
	2	0.0	1772.0	1688.4	945.0	2240.7
	3	0.0	256.2	1188.6	848.5	1245.0
Experimental Moisture removed (g)	1	0	470	86	5	-4
	2	0	459	122	1	3
	3	0	457	75	4	0
Percentage difference (%)	1	0.00	79.97	93.17	99.64	100.24
	2	0.00	74.10	92.77	99.89	99.87
	3	0.00	78.38	93.69	99.53	100.00

TableB-6: Moisture Properties for 20 ºC Temperature Setting

	Trial	20 ºC Time (hr) 0	1	2	3	4
Rate of Moisture Remove (kg/s)	1	1.47E-04	9.77E-05	4.03E-04	0.0006	6.31E-04
	2	-4.03E-04	1.95E-04	5.06E-04	0.0003	5.06E-04
	3	1.55E-04	7.45E-04	5.96E-04	0.0004	5.20E-04
Theoretical Moisture removed (g)	1	0.0	351.7	1450.4	2282.9	2269.9
	2	0.0	702.3	1819.9	1109.7	1821.0
	3	0.0	2683.1	2145.3	1495.9	1871.3
Experimental Moisture removed (g)	1	0	469	87	10	4
	2	0	476	99	10	-1
	3	0	451	114	16	10
Percentage difference (%)	1	0.00	33.37	94.00	99.56	99.82
	2	0.00	32.23	94.56	99.10	100.05
	3	0.00	83.19	94.69	98.93	99.47

TableB-7: Moisture Properties for 22 ºC Temperature Setting

	Trial	22 ºC				
		Time (hr)				
		0	1	2	3	4
Rate of Moisture Remove (kg/s)	1	-0.0002	0.0003	1.68E-04	2.05E-04	2.03E-04
	2	-0.0004	0.0001	3.56E-04	8.06E-04	4.77E-04
	3	-0.0001	0.0002	1.77E-04	3.84E-04	4.40E-04
Theoretical Moisture removed (g)	1	0.0	1032.2	603.5	736.8	730.3
	2	0.0	460.1	1282.4	2901.7	1715.7
	3	0.0	865.2	637.1	1383.5	1584.2
Experimental Moisture removed (g)	1	0	467	102	9	5
	2	0	462	82	12	5
	3	0	510	81	10	2
Percentage difference (%)	1	0.00	54.76	83.10	98.78	99.32
	2	0.00	0.41	93.61	99.59	99.71
	3	0.00	41.05	87.29	99.28	99.87

APPENDIX C: Results for Different Drying Loads

TableC-1: Mass Properties for Different Drying Loads

No. of clothes	Trial	Time	Mass of Clothes (g)							Moisture Added (g)	Time to dry (hr)	Drying Rate (kg/hr)	Moisture removed in 4 hours (g)
			Dry	Spin Dry	After Drying								
					0	1	2	3	4				
3	1	13:15	533	825	825	551	523	521	521	292	1.248	0.234	304
	2	8:35	535	841	841	547	527	525	525	306	1.158	0.264	316
	3	13:15	537	795	795	535	528	529	529	258	0.974	0.265	266
6	1	12:48	969	1508	1508	1039	952	942	938	539	1.547	0.3484	570
	2	13:12	1051	1602	1602	1126	1027	1017	1018	551	1.515	0.3637	584
	3	8:35	1051	1615	1615	1164	1050	1034	1024	564	1.974	0.2856	591
9	1	8:38	1439	2184	2184	1703	1465	1397	1391	745	2.217	0.336	793
	2	13:10	1438	2247	2247	1711	1492	1420	1411	809	2.608	0.310	836
	3	8:38	1424	2244	2244	1670	1492	1403	1408	820	2.724	0.301	836
12	1	10:45	2006	3075	3075	2651	2409	2162	2063	1069	-	-	1012
	2	11:00	1972	3092	3092	2459	2203	2023	1962	1120	3.383	0.331	1130
	3	10:40	1972	3072	3072	2457	2141	1985	1944	1100	3.142	0.350	1128

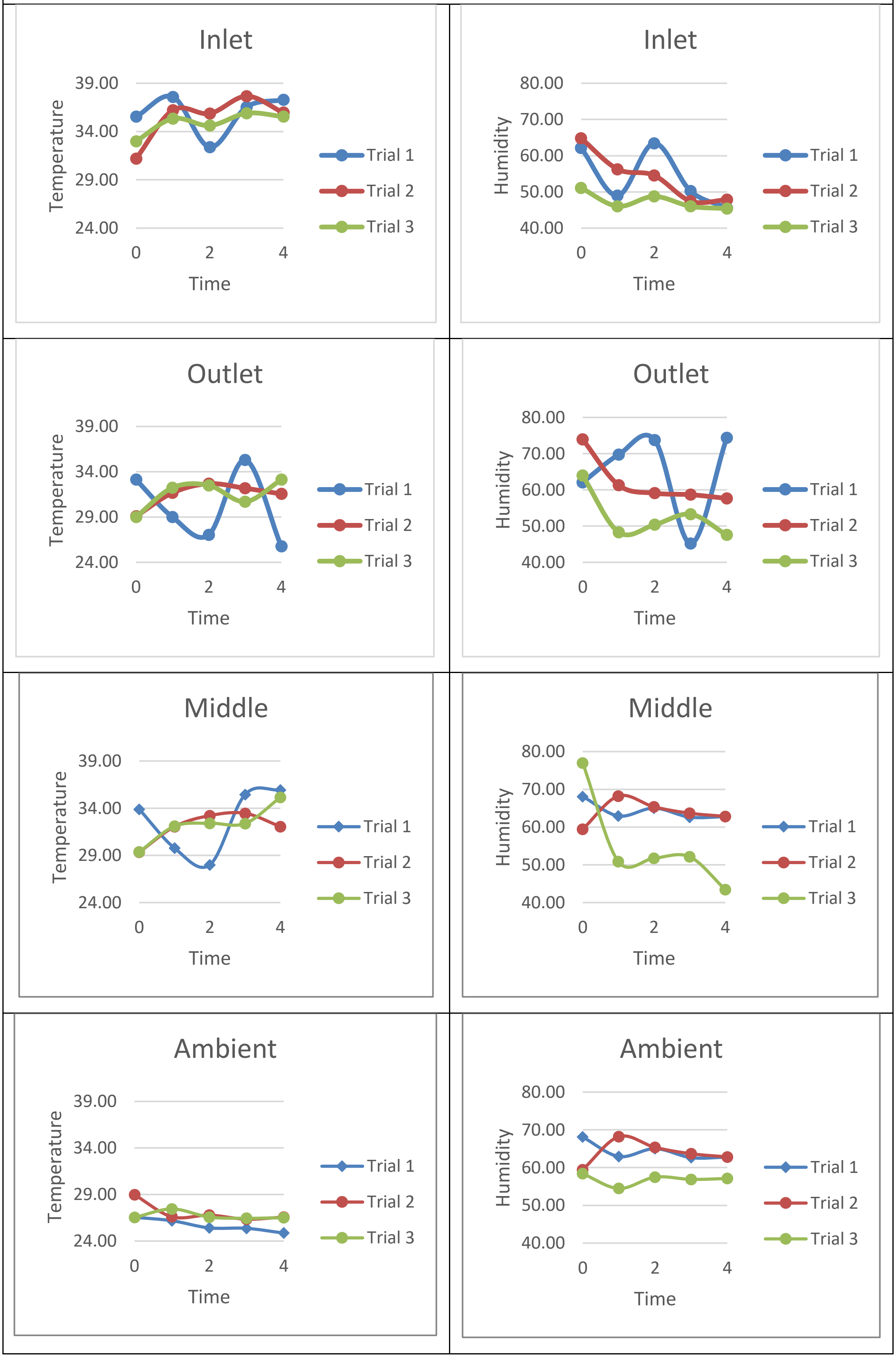
TableC-2: Drying Properties for Drying Load of 3 Pieces

			3 pieces				
			Time (hr)				
Position	Properties	Trial	0	1	2	3	4
Inlet	Temperature (ºC)	1	35.54	37.59	32.39	36.54	37.29
		2	31.20	36.22	35.87	37.66	35.96
		3	33.00	35.34	34.62	35.90	35.55
	Relative humidity (%)	1	62.15	49.00	63.45	50.25	45.58
		2	64.83	56.28	54.58	47.46	47.85
		3	51.11	46.06	48.77	46.03	45.41
	Fan speed (m/s)	1	7.8	8.2	7.9	7.8	8.1
		2	6.4	5.3	5.2	6.0	6.8
		3	5.7	6.4	6.4	5.2	6.5
	Specific volume (m^3/kg)	1	0.907	0.909	0.893	0.905	0.906
		2	0.888	0.907	0.904	0.908	0.901
		3	0.890	0.897	0.896	0.900	0.898
	Mass flowrate (kg/s)	1	0.220	0.231	0.227	0.221	0.229
		2	0.185	0.150	0.147	0.169	0.193
		3	0.164	0.183	0.183	0.148	0.185
	Specific humidity	1	0.023	0.020	0.020	0.020	0.018
		2	0.019	0.022	0.020	0.020	0.018
		3	0.016	0.017	0.017	0.017	0.017
Outlet	Temperature (ºC)	1	33.12	29.01	27.04	35.30	25.75
		2	29.08	31.67	32.68	32.18	31.55
		3	29.01	32.24	32.50	30.70	33.12
	Relative humidity (%)	1	62.09	69.74	73.74	45.20	74.37
		2	73.94	61.29	59.09	58.67	57.65
		3	63.93	48.31	50.39	53.27	47.55
	Fan speed (m/s)	1	1.5	1.0	0.0	0.0	0.0
		2	0.0	0.0	1.1	0.8	0.0
		3	0.0	0.0	1.4	0.0	1.4
	Specific volume (m^3/kg)	1	0.896	0.880	0.873	0.897	0.868
		2	0.882	0.889	0.892	0.890	0.887
		3	0.878	0.886	0.888	0.881	0.889
	Mass flowrate (kg/s)	1	0.475	0.322	0.000	0.000	0.000
		2	0.000	0.000	0.350	0.255	0.000
		3	0.000	0.000	0.447	0.000	0.446

	Specific humidity	1	0.020	0.018	0.017	0.016	0.016
		2	0.019	0.018	0.019	0.018	0.017
		3	0.016	0.015	0.016	0.015	0.015
Middle	Temperature (ºC)	1	33.88	29.77	28.00	35.45	35.95
		2	29.34	32.05	33.22	33.46	32.05
		3	29.37	32.09	32.41	32.38	35.15
	Relative humidity (%)	1	65.22	66.14	74.28	45.25	44.09
		2	75.29	64.79	58.17	55.46	55.48
		3	77.00	50.86	51.76	52.13	43.45
Ambient	Temperature (ºC)	1	26.56	26.19	25.42	25.37	24.86
		2	28.98	26.61	26.79	26.35	26.58
		3	26.53	27.45	26.58	26.45	26.51
	Relative humidity (%)	1	68.11	62.95	65.03	62.64	62.77
		2	59.45	68.21	65.36	63.67	62.83
		3	58.39	54.47	57.48	56.88	57.12

FigureC-1: Graphs of Drying Properties for Drying Load of 3 pieces

3 pieces



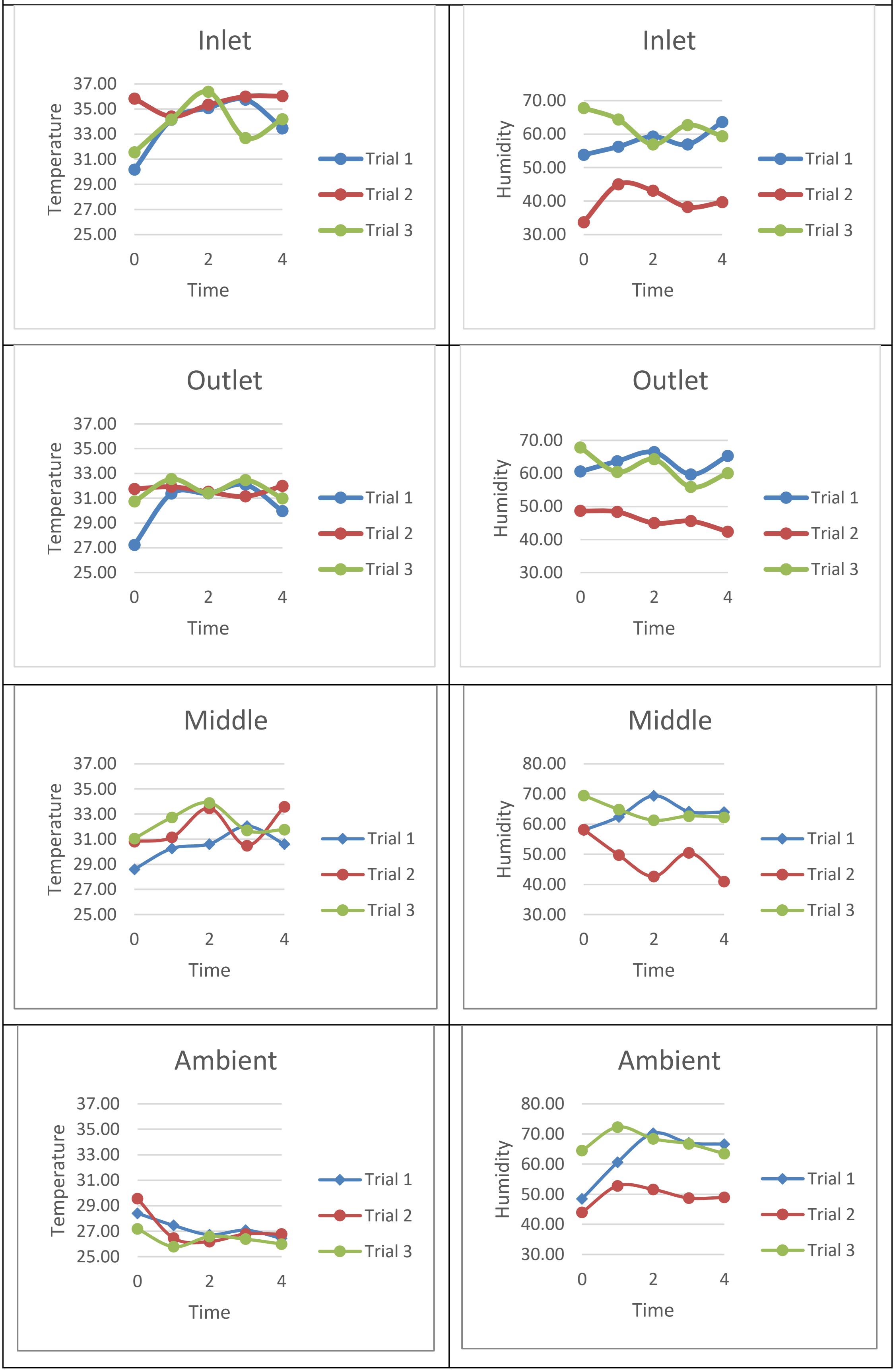
TableC-3: Drying Properties for Drying Load of 6 Pieces

			6 pieces				
			Time (hr)				
Position	Properties	Trial	0	1	2	3	4
Inlet	Temperature (ºC)	1	30.18	34.14	35.09	35.75	33.47
		2	35.82	34.41	35.34	36.00	36.03
		3	31.55	34.16	36.38	32.70	34.18
	Relative humidity (%)	1	53.82	56.27	59.29	56.93	63.64
		2	33.74	44.99	43.11	38.25	39.68
		3	67.80	64.40	56.93	62.72	59.38
	Fan speed (m/s)	1	6.3	5.7	7.1	7.0	6.5
		2	7.4	6.8	6.8	7.7	7.7
		3	6.0	8.2	6.4	5.8	5.7
	Specific volume (m^3/kg)	1	0.880	0.897	0.903	0.905	0.898
		2	0.893	0.893	0.896	0.896	0.897
		3	0.891	0.902	0.908	0.894	0.899
	Mass flowrate (kg/s)	1	0.183	0.163	0.201	0.198	0.185
		2	0.212	0.195	0.194	0.220	0.220
		3	0.173	0.233	0.181	0.166	0.162
	Specific humidity	1	0.014	0.019	0.021	0.021	0.020
		2	0.012	0.015	0.015	0.014	0.014
		3	0.019	0.022	0.022	0.019	0.020
Outlet	Temperature (ºC)	1	27.23	31.37	31.40	32.09	29.96
		2	31.75	31.92	31.51	31.15	31.99
		3	30.73	32.54	31.41	32.47	30.99
	Relative humidity (%)	1	60.57	63.71	66.42	59.71	65.31
		2	48.63	48.38	44.96	45.56	42.39
		3	67.82	60.45	64.26	55.88	60.09
	Fan speed (m/s)	1	0.4	0.4	0.0	0.0	1.0
		2	1.0	1.1	0.8	0.0	1.0
		3	1.6	1.5	1.0	0.0	0.0
	Specific volume (m^3/kg)	1	0.87	0.888	0.89	0.89	0.883
		2	0.884	0.884	0.881	0.88	0.882
		3	0.887	0.892	0.889	0.89	0.885
	Mass flowrate (kg/s)	1	0.130	0.128	0.000	0.000	0.321
		2	0.321	0.353	0.257	0.000	0.000
		3	0.511	0.477	0.319	0.000	0.000

	Specific humidity	1	0.013	0.018	0.019	0.018	0.017
		2	0.014	0.014	0.013	0.012	0.012
		3	0.019	0.018	0.018	0.017	0.017
Middle	Temperature (ºC)	1	28.61	30.26	30.62	32.04	30.61
		2	30.82	31.15	33.47	30.49	33.59
		3	31.05	32.74	33.90	31.70	31.76
	Relative humidity (%)	1	57.95	62.42	69.43	64.16	63.98
		2	58.20	49.74	42.65	50.49	41.00
		3	69.53	64.86	61.29	62.70	62.25
Ambient	Temperature (ºC)	1	28.40	27.45	26.72	27.07	26.44
		2	29.55	26.46	26.18	26.78	26.77
		3	27.18	25.78	26.58	26.37	25.99
	Relative humidity (%)	1	48.45	60.61	70.19	67.00	66.62
		2	43.96	52.80	51.60	48.73	48.93
		3	64.48	72.29	68.40	66.69	63.45

FigureC-2: Graphs of Drying Properties for Drying Load of 6 pieces

6 pieces



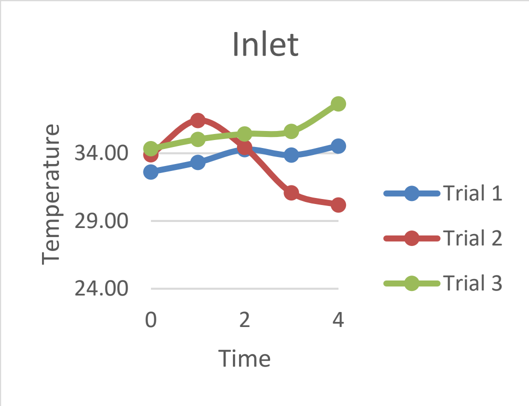
TableC-4: Drying Properties for Drying Load of 9 Pieces

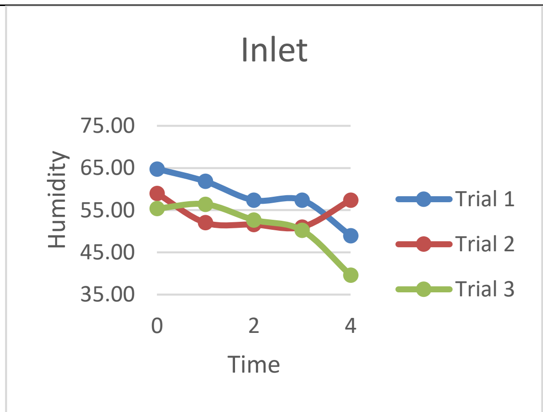
Position	Properties	Trial	9 pieces Time (hr) 0	1	2	3	4
Inlet	Temperature (ºC)	1	32.63	33.33	34.27	33.86	34.54
		2	33.89	36.43	34.43	31.08	30.19
		3	34.34	35.03	35.43	35.61	37.66
	Relative humidity (%)	1	64.79	61.84	57.36	57.40	48.99
		2	59.00	52.04	51.60	51.04	57.42
		3	55.38	56.42	52.70	50.22	39.58
	Fan speed (m/s)	1	7.9	7.8	7.2	8.3	7.4
		2	6.8	6.7	6.3	7.0	7.1
		3	6.3	5.3	6.0	6.3	6.3
	Specific volume (m^3/kg)	1	0.895	0.896	0.899	0.897	0.896
		2	0.898	0.905	0.896	0.882	0.881
		3	0.898	0.902	0.901	0.901	0.904
	Mass flowrate (kg/s)	1	0.226	0.223	0.205	0.237	0.212
		2	0.194	0.190	0.180	0.203	0.206
		3	0.180	0.151	0.171	0.179	0.179
	Specific humidity	1	0.020	0.020	0.020	0.019	0.017
		2	0.020	0.020	0.018	0.015	0.016
		3	0.019	0.020	0.019	0.019	0.016
Outlet	Temperature (ºC)	1	31.29	31.60	32.78	32.82	33.64
		2	30.63	33.16	31.45	27.04	30.79
		3	31.10	32.72	33.38	32.98	34.03
	Relative humidity (%)	1	72.60	62.41	56.30	54.94	49.00
		2	69.92	59.52	53.21	62.67	48.54
		3	68.44	62.77	54.37	54.97	45.79
	Fan speed (m/s)	1	0.8	0.8	0.8	0.0	1.7
		2	0.0	1.1	0.0	1.5	0.8
		3	1.9	1.6	1.1	1.1	1.7
	Specific volume (m^3/kg)	1	0.892	0.889	0.891	0.891	0.892
		2	0.888	0.895	0.884	0.870	0.880
		3	0.889	0.894	0.893	0.892	0.892
	Mass flowrate (kg/s)	1	0.254	0.255	0.255	0.000	0.540
		2	0.000	0.348	0.000	0.489	0.258
		3	0.606	0.507	0.349	0.350	0.540

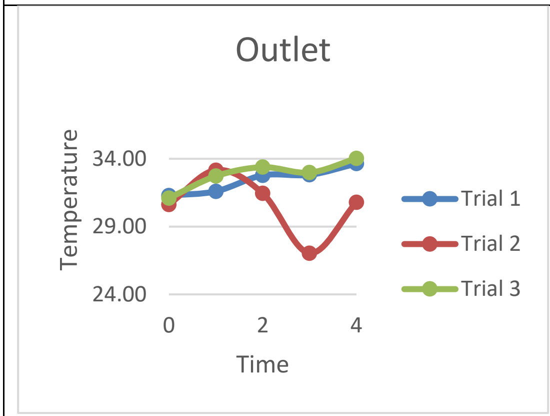
	Specific humidity	1	0.021	0.018	0.018	0.017	0.016
		2	0.020	0.019	0.015	0.014	0.014
		3	0.020	0.020	0.018	0.017	0.015
Middle	Temperature (ºC)	1	30.84	32.91	34.93	34.36	34.43
		2	33.68	37.21	33.02	27.53	30.43
		3	30.55	33.56	34.57	33.31	33.11
	Relative humidity (%)	1	77.51	59.82	50.72	49.20	48.32
		2	59.64	46.93	53.89	55.40	49.32
		3	71.71	61.04	52.47	53.64	49.81
Ambient	Temperature (ºC)	1	26.38	24.30	24.74	24.84	24.74
		2	26.53	26.60	26.13	24.99	25.58
		3	26.45	26.93	26.50	26.88	26.23
	Relative humidity (%)	1	76.93	68.50	65.68	64.76	64.78
		2	67.60	65.47	59.79	57.66	55.37
		3	63.67	65.15	65.08	60.37	57.50

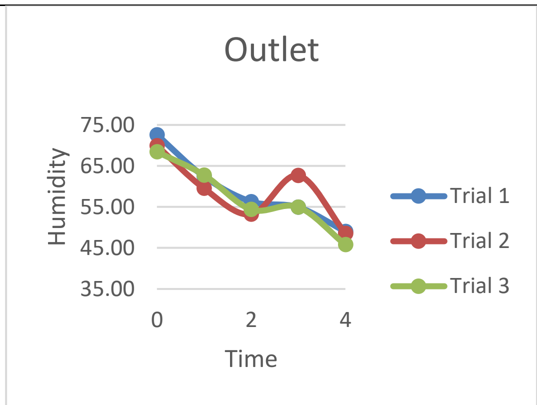
FigureC-3: Graphs of Drying Properties for Drying Load of 9 pieces

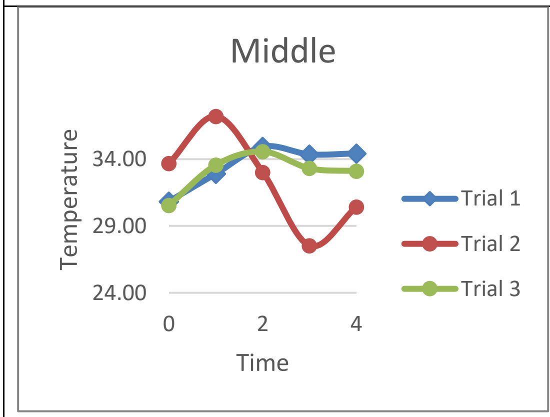
9 pieces

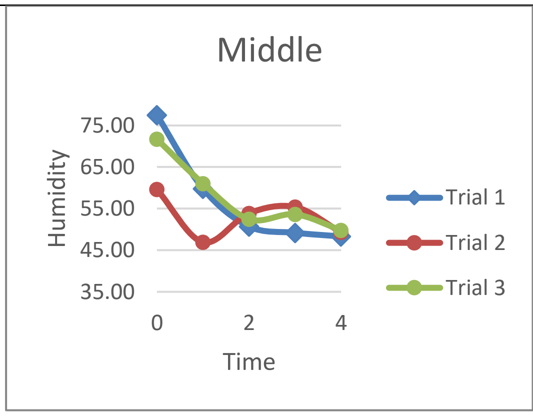


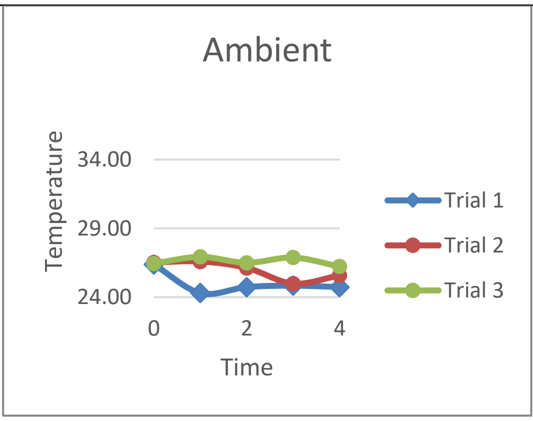


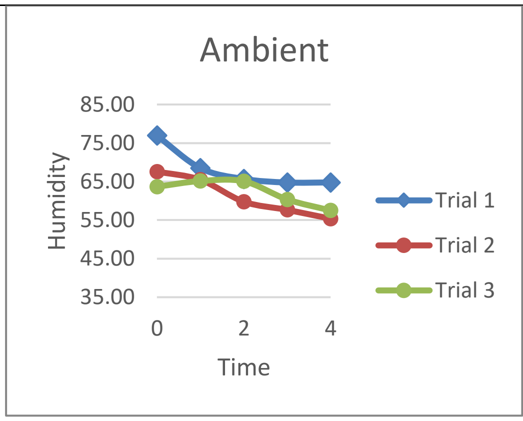












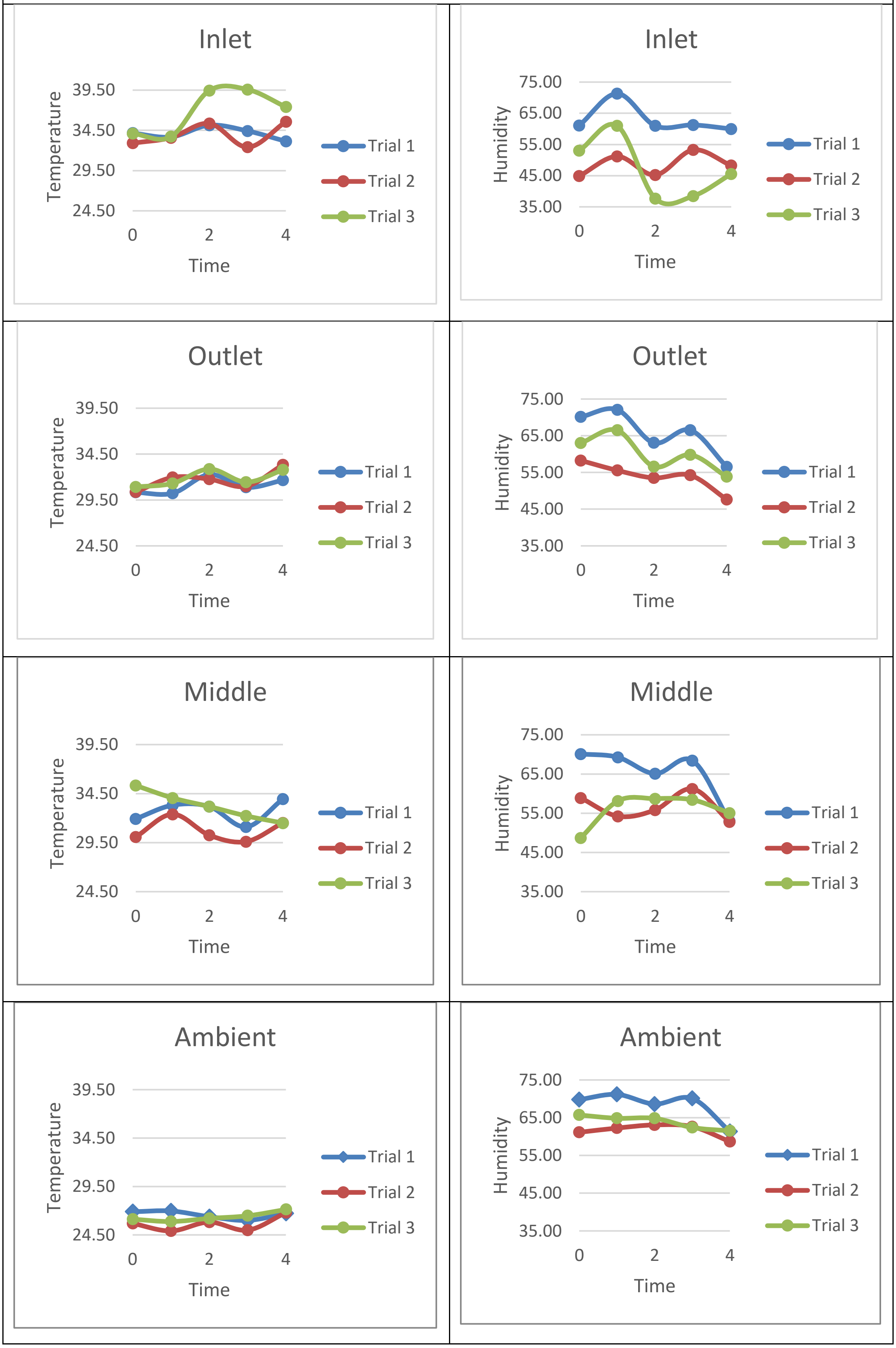
TableC-5: Drying Properties for Drying Load of 12 Pieces

			12 pieces				
			Time (hr)				
Position	Properties	Trial	0	1	2	3	4
Inlet	Temperature (ºC)	1	34.16	33.68	35.14	34.43	33.14
		2	32.91	33.59	35.36	32.41	35.59
		3	34.11	33.72	39.45	39.58	37.41
	Relative humidity (%)	1	61.07	71.31	60.98	61.26	59.99
		2	44.88	51.18	45.22	53.27	48.25
		3	53.02	61.00	37.68	38.49	45.53
	Fan speed (m/s)	1	5.4	5.6	5.0	4.9	4.8
		2	6.5	6.0	5.8	7.1	6.0
		3	6.0	6.4	6.7	6.8	6.5
	Specific volume (m^3/kg)	1	0.900	0.903	0.904	0.901	0.895
		2	0.887	0.893	0.897	0.889	0.900
		3	0.896	0.898	0.910	0.911	0.906
	Mass flowrate (kg/s)	1	0.154	0.159	0.142	0.139	0.137
		2	0.188	0.172	0.166	0.205	0.171
		3	0.172	0.183	0.189	0.191	0.184
	Specific humidity	1	0.021	0.024	0.022	0.021	0.019
		2	0.014	0.017	0.016	0.016	0.018
		3	0.018	0.020	0.017	0.018	0.019
Outlet	Temperature (ºC)	1	30.33	30.23	32.27	30.88	31.65
		2	30.36	31.96	31.77	30.99	33.34
		3	30.92	31.31	32.87	31.45	32.77
	Relative humidity (%)	1	70.14	72.08	63.06	66.54	56.51
		2	58.25	55.56	53.52	54.23	47.64
		3	63.02	66.49	56.61	59.81	53.82
	Fan speed (m/s)	1	1.1	0.0	1.7	0.0	2.6
		2	1.0	1.4	1.7	0.0	1.3
		3	1.3	1.7	0.0	0.0	0.0
	Specific volume (m^3/kg)	1	0.886	0.887	0.892	0.887	0.887
		2	0.882	0.888	0.886	0.883	0.890
		3	0.886	0.889	0.892	0.887	0.890
	Mass flowrate (kg/s)	1	0.352	0.000	0.540	0.000	0.831
		2	0.321	0.447	0.544	0.000	0.414
		3	0.416	0.542	0.000	0.000	0.000

	Specific humidity	1	0.019	0.020	0.019	0.019	0.017
		2	0.016	0.017	0.016	0.015	0.015
		3	0.018	0.019	0.018	0.017	0.017
Middle	Temperature (ºC)	1	31.93	33.32	33.18	31.11	33.96
		2	30.08	32.40	30.26	29.61	31.53
		3	35.33	34.06	33.18	32.23	31.50
	Relative humidity (%)	1	70.11	69.26	65.08	68.44	53.01
		2	58.91	54.24	55.85	61.21	52.82
		3	48.71	58.14	58.73	58.42	55.05
Ambient	Temperature (ºC)	1	26.89	26.97	26.38	26.00	26.71
		2	25.69	24.91	25.82	24.99	26.80
		3	26.12	25.88	26.20	26.47	27.12
	Relative humidity (%)	1	69.80	71.17	68.62	70.10	61.34
		2	61.13	62.25	63.09	62.63	58.68
		3	65.71	64.85	64.83	62.39	61.51

FigureC-4: Graphs of Drying Properties for Drying Load of 12 pieces

12 pieces



TableC-6: Moisture Properties for Drying Load of 3 Pieces

	Trial	3 pieces Time (hr) 0	1	2	3	4
Rate of Moisture Remove (kg/s)	1	6.61E-04	5.55E-04	6.57E-04	7.07E-04	6.64E-04
	2	-3.69E-05	5.09E-04	2.80E-04	3.05E-04	1.93E-04
	3	1.64E-05	3.66E-04	2.56E-04	3.55E-04	2.60E-04
Theoretical Moisture removed (g)	1	0.0	1996.8	2366.2	2543.8	2391.3
	2	0.0	1832.4	1008.0	1097.0	696.1
	3	0.0	1316.1	1844.6	3836.9	3738.6
Experimental Moisture removed (g)	1	0	274	28	2	0
	2	0	294	20	2	0
	3	0	260	7	-1	0
Percentage difference (%)	1	0.00	86.28	98.82	99.92	100.00
	2	0.00	83.96	98.02	99.82	100.00
	3	0.00	80.25	99.62	100.03	100.00

TableC-7: Moisture Properties for Drying Load of 6 Pieces

	Trial	6 pieces Time (hr) 0	1	2	3	4
Rate of Moisture Remove (kg/s)	1	2.41E-04	6.52E-04	3.50E-04	3.89E-04	4.71E-04
	2	-1.69E-04	4.92E-04	4.69E-04	2.62E-04	6.22E-04
	3	1.00E-04	7.12E-05	3.30E-04	2.36E-04	3.46E-04
Theoretical Moisture removed (g)	1	0.0	2345.9	1260.0	1401.9	1694.0
	2	0.0	1772.0	1688.4	945.0	2240.7
	3	0.0	256.2	1188.6	848.5	1245.0
Experimental Moisture removed (g)	1	0	470	86	5	-4
	2	0	459	122	1	3
	3	0	457	75	4	0
Percentage difference (%)	1	0.00	79.97	93.17	99.64	100.24
	2	0.00	74.10	92.77	99.89	99.87
	3	0.00	78.38	93.69	99.53	100.00

TableC-8: Moisture Properties for Drying Load of 9 Pieces

	Trial	9 pieces Time (hr) 0	1	2	3	4
Rate of Moisture Remove (kg/s)	1	-2.04E-04	4.01E-04	3.90E-04	4.50E-04	1.69E-04
	2	5.82E-05	1.90E-04	4.32E-04	8.13E-05	4.13E-04
	3	-1.08E-04	7.53E-05	2.56E-04	1.97E-04	1.43E-04
Theoretical Moisture removed (g)	1	0.0	1445.2	1403.5	1621.5	609.4
	2	0.0	682.8	1556.4	292.8	1486.6
	3	0.0	271.0	1842.6	2128.2	2056.9
Experimental Moisture removed (g)	1	0	481	238	68	6
	2	0	536	219	72	9
	3	0	574	178	89	-5
Percentage difference (%)	1	0.00	66.72	83.04	95.81	99.02
	2	0.00	21.50	85.93	75.41	99.39
	3	0.00	111.83	90.34	95.82	100.24

TableC-9: Moisture Properties for Drying Load of 12 Pieces

	Trial	12 pieces Time (hr) 0	1	2	3	4
Rate of Moisture Remove (kg/s)	1	2.46E-04	6.67E-04	3.83E-04	3.34E-04	3.71E-04
	2	-3.38E-04	3.44E-05	9.94E-05	2.05E-04	3.93E-04
	3	1.72E-05	1.83E-04	-1.70E-04	1.91E-05	2.94E-04
Theoretical Moisture removed (g)	1	0.0	2402.3	1377.4	1203.8	1335.6
	2	0.0	123.9	357.8	736.6	1414.2
	3	0.0	657.3	-1222.3	206.5	4234.9
Experimental Moisture removed (g)	1	0	424	242	247	99
	2	0	633	256	180	61
	3	0	615	316	156	41
Percentage difference (%)	1	0.00	82.35	82.43	79.48	92.59
	2	0.00	410.73	28.46	75.56	95.69
	3	0.00	6.44	125.85	24.47	99.03

APPENDIX D: Results for a Sealed and Unsealed Inlet

TableD-1: Mass Properties for a Sealed and Unsealed Inlet

No. of clothes	Time	Mass of Clothes (g)							Moisture Added (g)	Time to dry (hr)	Drying Rate (kg/hr)	Moisture removed in 4 hours
		Dry	Spin Dry	After Drying								
				0	1	2	3	4				
Sealed	8:38	1439	2184	2184	1703	1465	1397	1391	745	2.217	0.336	793
Unsealed	8:35	1458	2276	2276	1881	1641	1486	1438	818	3.287	0.249	838

TableD-2: Drying Properties for a Sealed and Unsealed Inlet

		Sealed					Unsealed				
		Time (hr)					Time (hr)				
Position	Properties	0	1	2	3	4	0	1	2	3	4
Inlet	Temperature (°C)	32.63	33.33	34.27	33.86	34.54	34.66	33.3	37.66	36.34	39.75
	Humidity (%)	64.79	61.84	57.36	57.4	48.99	58.88	72.56	56.56	64.89	49.26
	Fan speed (m/s)	7.9	7.8	7.2	8.3	7.4	6	5	6.4	4.6	5.7
Outlet	Temperature (°C)	31.29	31.6	32.78	32.82	33.64	30.85	32.55	35.73	35.41	37.95
	Humidity (%)	72.6	62.41	56.3	54.94	49	76.65	72.69	61.55	61.64	53.55
	Fan speed (m/s)	0.8	0.8	0.8	0	1.7	1.6	1.4	1	0	0
Middle	Temperature (°C)	30.84	32.91	34.93	34.36	34.43	33.56	32.93	34.39	35.37	38.91
	Humidity (%)	77.51	59.82	50.72	49.2	48.32	58.76	65.25	64.22	57.3	47.4
Ambient	Temperature (°C)	26.38	24.3	24.74	24.84	24.74	27.65	26.11	26.28	26.22	26.43
	Humidity (%)	76.93	68.5	65.68	64.76	64.78	69.62	78.05	77.71	77.22	73.44

FigureD-1: Graphs of Drying Properties for a Sealed and Unsealed Inlet

Sealed and Unsealed