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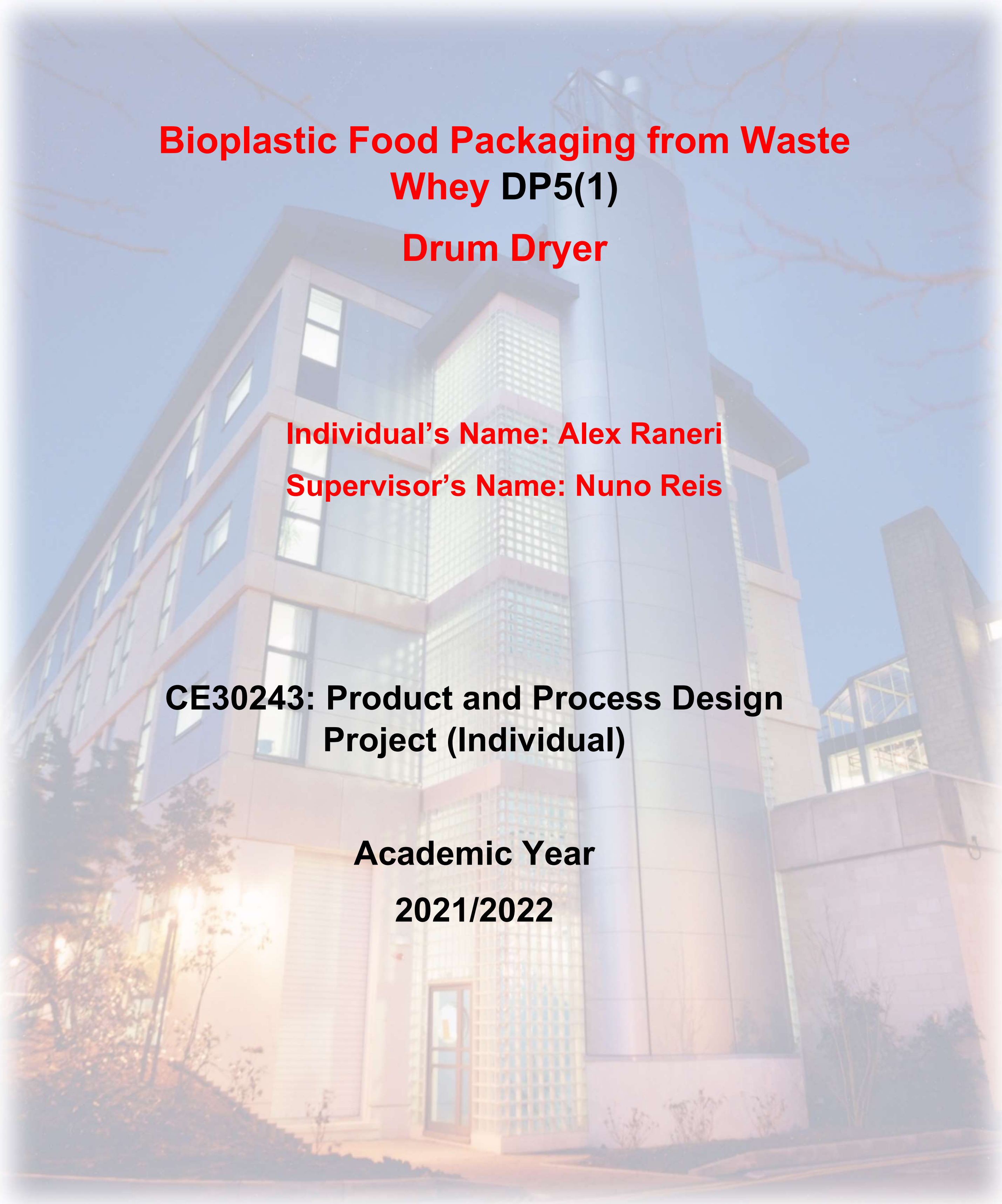

Bioplastic Food Packaging from Waste Whey DP5(1)

Drum Dryer

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CE30243: Product and Process Design Project (Individual)

Academic Year
2021/2022

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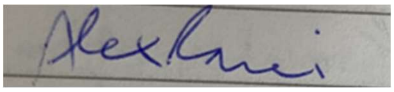
Signature: 

Date: 05/05/2022

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Nomenclature

Table 0.1: P&ID Symbols

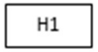
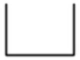
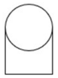
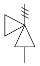
Symbol	Equipment	Symbol	Equipment
	Pump		Screw-down Valve
	Motor		Diaphragm Valve (Fail Open)
	Induction Heater		Temperature Indicating Control
	Condensate Trap		Flow Indicating Control
	Sampling Point		Pressure Indicating Control
	Drum Dryer		Temperature Transmitter
	Process Flows		Flow Transmitter
	Electrical Signal		Level Transmitter
	Process Inflows and Outflows		Level Low Alarm
	Y-Strainer Valve		Level High Alarm
	Pressure Relief Valve		Level High Cut Off
	Temperature High Alarm		Pressure High Alarm

Table 0.2: Nomenclature

Symbol	Definition	Unit
A	Area	m^2
C_{knife}	Knife heat capacity	$J\ K^{-1}\ kg^{-1}$
C_p	Element heat capacity	$J\ K^{-1}\ kg^{-1}$
$C_{p,air}$	Air heat capacity	$J\ K^{-1}\ kg^{-1}$
C_{ps}	Plastic heat capacity	$J\ K^{-1}\ kg^{-1}$
C_{pw}	Moisture heat capacity	$J\ K^{-1}\ kg^{-1}$
c_{air}	Air molar concentration	$mol\ m^{-3}$
c_p	Specific heat capacity	$J\ K^{-1}\ kg^{-1}$
$D_{w,air}$	Moisture diffusivity in air	$m^2\ s^{-1}$
D_{we}	Moisture diffusivity in element	$m^2\ s^{-1}$
D_1	Inner diameter	m
d	Element thickness	m
d_0	Initial feed layer thickness	m
E	Welding Factor	-
E_v	Evaporation rate	$kg\ s^{-1}$
F	Force	N
F_i	Flow rate of stream i	$tonnes\ batch^{-1}$
G	Mass flowrate of steam	$kg\ m^{-2}\ s^{-1}$
G_m	Air molar flux	$mol\ m^{-2}\ s^{-1}$
h	Air convective heat transfer coefficient	$W\ m^{-2}\ K^{-1}$
h_{fg}	Specific enthalpy	kJ/kg
Δh	Friction loss of pipe	m
K_G	Mass transfer coefficient from element surface to air	$mol\ atm^{-1}\ m^{-2}\ s^{-1}$
k	Element thermal conductivity	$W\ m^{-1}\ K^{-1}$
k_{air}	Air thermal conductivity	$W\ m^{-1}\ K^{-1}$
k_d	Drum thermal conductivity	$W\ m^{-1}\ K^{-1}$
k_{knife}	Knife thermal conductivity	$W\ m^{-1}\ K^{-1}$
k_s	Plastic thermal conductivity	$W\ m^{-1}\ K^{-1}$
k_w	Moisture thermal conductivity	$W\ m^{-1}\ K^{-1}$
k_{wear}	Wear coefficient	$mm^3\ N^{-1}\ m^{-1}$
L	Length	m
ΔL	Change in Length	m
M	Moisture molecular weight	$g\ mol^{-1}$
MTR	Mass transfer rate	$mol\ m^{-2}\ s^{-1}$
m	Mass	kg
$\dot{m}$	Mass flow	$kg\ batch^{-1}$
P	Pressure	Pa
P_{LMTD}	Ratio for correction factor	-
P_w	Moisture partial pressure in air	atm
P^{sat}	Saturation pressure at element temperature	atm
ΔP	Pressure difference	Pa
ΔP_{loss}	Pressure loss of pipe	Pa
Q	Heat transfer	kJ
$\dot{Q}$	Rate of heat transfer	kW
R_1	Drum inside radius	m
R_2	Drum outside radius	m
S	Maximum allowable stress	psi
T	Temperature	K
T_B	Cylinder internal surface temperature	K
ΔT	Change in Temperature	K

ΔT_{lm}	Log mean temperature difference	K
t	Time	s
t_c	Metal thickness	m
Δt	Change in time	s
U	Heat transfer coefficient	W m^{-2} K^{-1}
u_{air}	Air velocity	m s^{-1}
V_{rc}	Drum rotation velocity	s^{-1}
v	Drum rotation velocity	m s^{-1}
X	Moisture content	kg kg^{-1}
Δx	Drum metal thickness	m
α	Solid phase volume in element	-
$\alpha_{expansion}$	Thermal Expansion Coefficient	K^{-1}
μ_{air}	Air viscosity	N s m^{-2}
$\mu_{friction}$	Coefficient of Friction	-
ξ	Evaporation rate reduction factor	-
ρ	Element density	kg m^{-3}
ρ_{air}	Air density	kg m^{-3}
ρ_f	Feed density	kg m^{-3}
ρ_{knife}	Knife density	kg m^{-3}
ρ_s	Plastic density	kg m^{-3}
ρ_w	Moisture density	kg m^{-3}
σ	Normal Stress	Pa

Subscript	Definition
c	Cold
h	Hot
i	In
o	Out

List of Acronyms

Table 0.3: List of Acronyms

Acronym	Meaning
AISI	American Iron and Steel Institute
ASME	American Society of Mechanical Engineers
BS	British Standard
EFSA	European Food Safety Authority
FCM	Food Contact Materials
HAZID	Hazard Identification
HAZOP	Hazard and Operability Analysis
IPL	Independent Protection Layer
LMTD	Log Mean Temperature Difference
LOPA	Layer of Protection Analysis
NaN	Not a Number
PEGMA	Poly(ethylene glycol) methacrylate
PFD	Probability of Failure on Demand
PFD	Process Flow Diagram
PHB	Polyhydroxy butyrate
PID	Proportional-Integral-Derivative
PRV	Pressure Relief Valve
P&ID	Piping and Instrumentation Diagram

Executive Summary

The objective of the project was to produce a waste-to-high value bioplastic relevant to at least three items on the environmental agenda at COP26; moving away from fossil fuel-based products, prevention of single-use plastics, and reducing waste. A bioplastic film for food packaging was designed from unused whey sourced from farmers in Somerset; preventing food waste and the illegal disposal of whey, which can cause habitat damage. Project aims included having smaller carbon emissions than fossil fuel-based plastics, boosting Somerset's local economy and creating a profitable business.

In initial scoping studies, various methods were investigated to convert waste whey to bioplastic, including using fermentation or co-polymerisation processes. After considering sustainability, cost, risk, process yield and product quality, the chosen option was a co-polymerisation reaction with poly(ethylene glycol) methacrylate (PEGMA) using waste liquid whey. This produced shaved flakes of a polyethylene-like plastic, consisting of a protein to PEGMA ratio of 30:70, selected for its mechanical properties. Literature describing the lab scale process (Chalermthai et al., 2019) and the industrial units for scale up of the process (Chalermthai et al., 2020) were available. Further processing of the plastic to produce a film was conducted by a partner company. The feedstock for the process was 44,800 tonnes of waste whey, corresponding to 1.05% of the total produced in the UK.

The process involved liquid whey processing, whey powder generation, chemical processing, and plastic production steps. 100 tonnes of whey were processed per batch, thus 448 batches per year, amounting to 3 batches run each day in series. 2.515 tonnes of plastic were produced from each batch, yielding 1126.7 tonnes of plastic product per year. The plastic had a water content of 9% and small quantities of impurities: carbohydrates, fats, and minerals from the raw feedstock protein along with unreacted species from the chemical processing.

The safety aspects of the process require re-evaluation for a more in-depth risk analysis, including in-depth risk quantification and LOPA analysis, which this report details in **Section 5.2**. The environmental impact of the process was assessed by consideration of the sourcing of the inputs into the system, the operations of the process and the waste created from the process. Large contributors to the carbon footprint included water and steam requirements, as well as the use of PEGMA and methacrylic anhydride, whereas transport had a reduced impact due to sourcing locally.

The total capital cost was estimated as £31.03 million. The total operating costs were estimated as £3.084 million. The purchasing raw materials makes up the majority as the annual cost of PEGMA is £2.478 million. The annual income was £5.518 million, and the annual profit £2.434 million. The lifetime of the plant was estimated as 35 years. The net present value of the project at end of plant lifetime was calculated as -£2.673 million. Therefore, with the current set operating conditions of the plant, the process is not economically viable.

The designed process was taken as an initial short cut design; due to the timeframe in which the design was completed, various assumptions were applied. Assumptions mainly served to simplify balances and calculations, to eliminate the need for software-aided calculations. For the drum dryer the following assumptions were made; these assumptions are rejected or validated in individual detailed design:

- The specific heat of the plastic and washing requirements were assumed to be equal to that of PHB.
- Dimensions were taken from an average of literature values.
- The steam temperature heating the drum dryer was set at 150℃.
- Temperature increase due to friction between the blade and the plastic or drum were neglected.
- The dryer inlet stream comprised 40% water by weight. 85% of water in the dryer inlet stream was evaporated.
- Mass of polymer and impurities was conserved throughout drying.
- Isobaric operation at atmospheric pressure for the cold stream (the polymer/plastic). Condensate pressure was at atmospheric conditions.
- The drum dryer was treated as a counter flow heat exchanger.
- Overall heat transfer coefficient was assumed to lie within the range for steam heating a very viscous fluid. As the plastic was mostly solid, it was treated as a slurry. The value was assumed 600 W m^{-2} K^{-1}.
- Streams 40 and 42 do not enter contact with streams 39, 41 and 43; masses of streams 40 and 42 are equal.

A Process Flow Diagram (PFD) is presented below, **Figure 0.1**. The drum dryer is in section D of the process, plastic production.

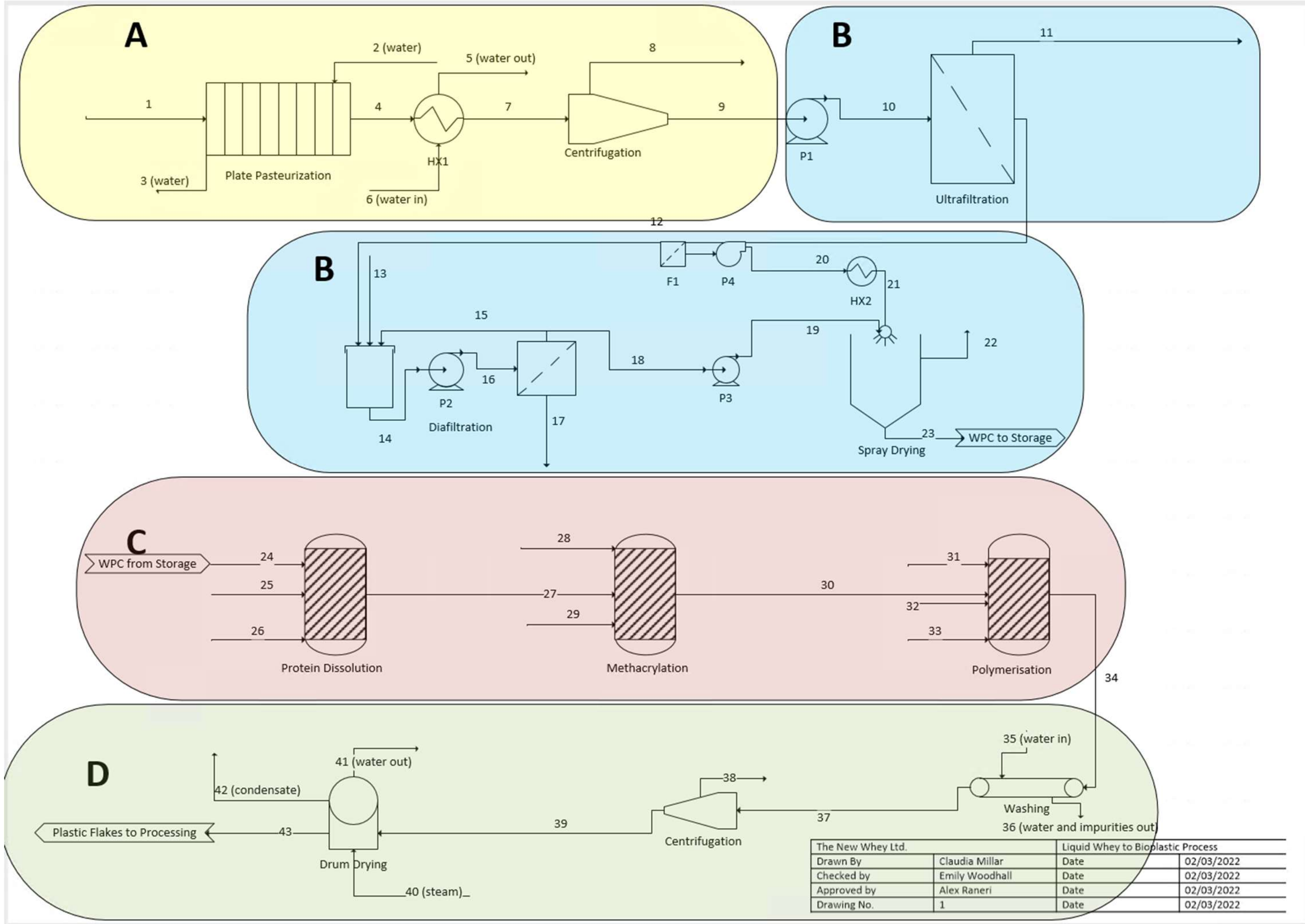


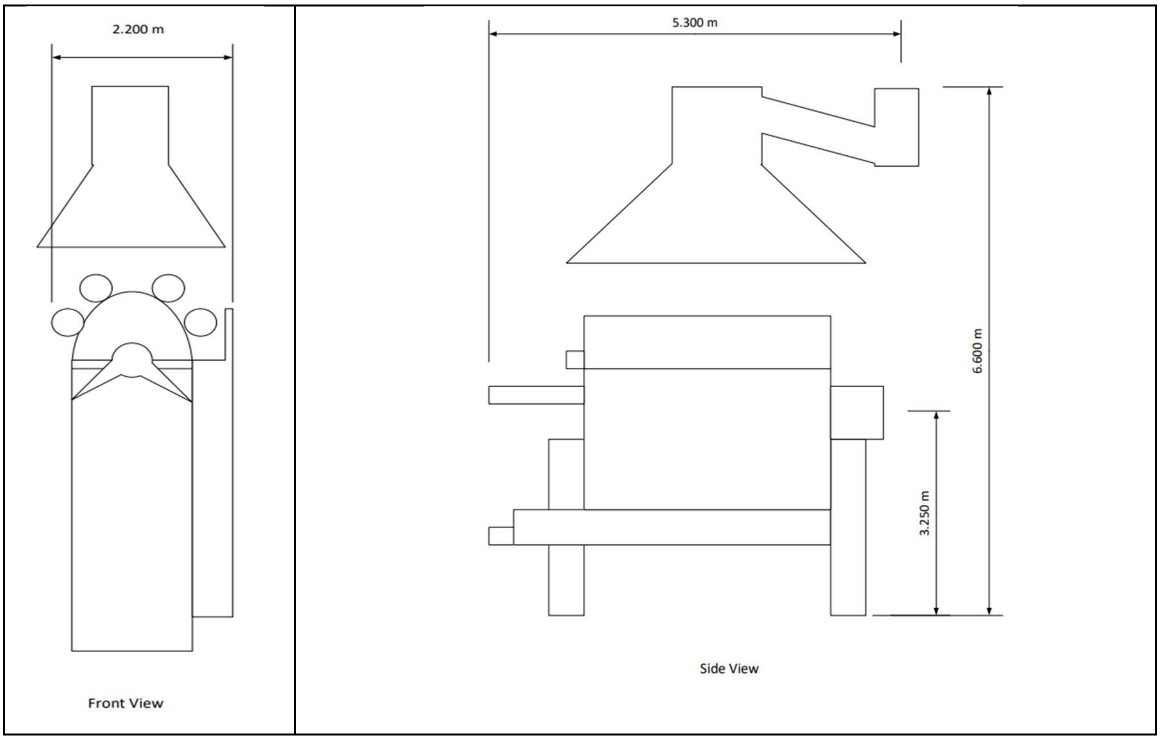
Figure 0.1: PFD for the Process, where section A is the pre-treatment, B is the production of whey powder, C is the chemical processing and D is the plastic production

Unit Design Brief

The drum dryer unit specification sheet as set by the design group is presented in **Table 0.4**.

Table 0.4: Group Design Drum Dryer Specification Sheet

Specification Sheet			Document Number:	
			Revision:	Status:
Operation	Plastic Making		Date: 10/03/2022	
Unit	Drum Dryer with Knife			
Service	Production of dried plastic flakes through evaporation			
Process Data				
Bioplastic			*Power Requirement*	
Inlet	3.81	tonnes $batch^{-1}$	Drive Power	33 kW min
Outlet	2.515	tonnes $batch^{-1}$		60 kW max
Steam/Condensate				
Inlet	4.23	tonnes $batch^{-1}$		
Outlet	4.23	tonnes $batch^{-1}$		
Operating Conditions				
Pressure	1	atm		
Bioplastic In	25	℃		
Bioplastic Out	72	℃		
Steam In	150	℃		
Water Out	96.43	℃		
Batch time	6	hours		
Mechanical Design				
Equipment Type	Single Drum Dryer Heat Exchanger			
Material	Type 304 Stainless Steel			
Dimension				
Equipment Volume	76.96	m^3		
Drum Diameter	1250	mm		
Drum Length	3000	mm		
Drying Surface Area	12	m^2		
Number of Applicator Rolls	4	-		
Applicator Roll Diameter	240	mm		
Unit Length	5300	mm		
Unit Width	2200	mm		
Unit Height	6600	mm		
Drum Heart Line	3250	mm		
Total Weight	32	tonnes		



1. Introduction

The project is a continuation from the Group Design Report, where the production of bioplastic from waste cheese whey was designed. The design of the drum dryer unit, used in drying polymer to produce the plastic, is undertaken, and developed in this report. Initial Group Design consisted of a broad overview of units; thus, the goal of this Individual Project is to explore the drum dryer in depth.

“The New Whey to Bioplastics” is the project developed by the group to produce plastic for food packaging applications, from waste cheese whey. The creation of plastics from food waste avoids use of petrochemicals, thus benefiting the environment, as well as avoiding feedstock produced specifically for the plastic, which takes up land that could be used instead to grow food. It was concluded that the project was not profitable, however, thus optimisation must seek to reduce costs.

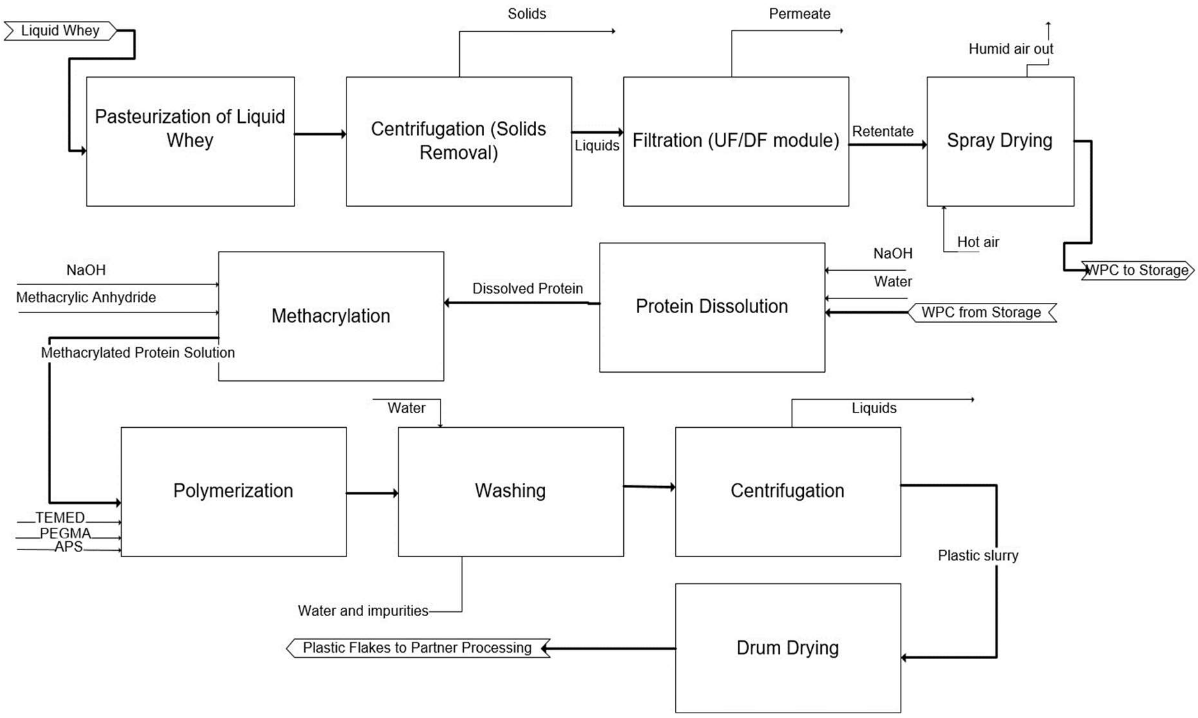


Figure 1.1: Simple Flowsheet of the Process

The process consists of 11 unit operations, shown in **Figure 1.1**. Pasteurisation removes any pathogens from the whey, centrifugation removes large solids such as fat. Ultrafiltration separates the whey protein from the lactose and other solutes. Diafiltration concentrates the protein and achieves a higher purity. Spray drying produces whey protein powder with a moisture content of around 10% - sufficient for plastic production. The powder is then dissolved in water. Methacrylation and polymerisation form the final polymer. The plastic is then washed to remove any unreacted components or impurities, centrifuged, and drum dried to remove excess water. Drum drying produces plastic flakes that a partner company processes into a film for food packaging.

The drum dryer consists of a rotating drum, where the polymer is fed onto the outside. Steam heats the drum from within, thus drying the polymer. Water evaporates and is removed by a vapour hood above the drum. After three-quarters of a turn from feed position, a doctor knife scrapes the dried polymer off the drum, forming plastic flakes. These are collected in a product bin. The drum dryer's role is thus to remove water and create flakes of product. Moisture composition of the plastic is subject to drum drying, thus variation in steam temperatures or pressures, as well as rotation speed, influence water evaporation from the polymer. Thickness of the plastic is also dependent on the dryer, it is influenced by steam, rotation speed, and feed application. Drum dryers have widespread application in the food industry (ANDRITZSeparation, 2014), thus their application to produce food packaging is deemed suitable. Use of materials in the drum and knives must adhere to food contact material safety standards, detailed in **Section 4.1** and **Section 4.4**.

Figure 1.2: a. Drum Dryer Schematic b. Photo of Drum Dryer (ANDRITZSeparation, 2014)

Calculations regarding material and energy balances around the dryer in the Group Report are checked:

"*Centrifuged polymer stream:* $F_{39} = 3.81\ tonnes\ batch^{-1}$"

"*The centrifuge reduces the water content of the polymer stream, to 40% (Chalermthai et al., 2020). Therefore, 1.524 tonnes of stream 39 is water, and 2.286 tonnes is the polymer and impurities.*"

$$3.81\ tonnes\ batch^{-1} \times 0.4 = 1.524\ tonnes\ batch^{-1}\ of\ water$$

$$3.81\ tonnes\ batch^{-1} - 1.524\ tonnes\ batch^{-1} = 2.286\ tonnes\ batch^{-1}\ of\ polymer\ and\ impurities$$

"*In the drum dryer, 85% of the water in the centrifuged content is evaporated (Chalermthai et al., 2020).*"

"*Amount of water removed in drum dryer:* $F_{41} = 1.295\ tonnes\ batch^{-1}$"

$$F_{41} = 1.524 \times 0.85 = 1.295\ tonnes\ batch^{-1}$$

"*Amount of water in final product:* $F_{43,water} = 0.2286$"

$$F_{43,water} = 1.524 - 1.295 = 0.2286$$

"*From this water removal, the total product per batch can be found:* $F_{43} = 2.515\ tonnes\ batch^{-1}$"

$$F_{43} = 0.2286 + 2.286 = 2.515\ tonnes\ batch^{-1}$$

"*The product has a moisture content of 9%, and a solids content (polymer and impurity) of 91%.*"

$$\frac{0.2286}{2.515} = 0.09089 \approx 9\%\ moisture$$

$$100\% - 9\% = 91\%\ solids$$

Thus, calculation checks agree with the Group Report. Energy balances are presented in **Section 2.2.2**, they are identical to the Group Report calculations.

However, from the Group P&ID, **Figure 1.3** is taken for the drum dryer:

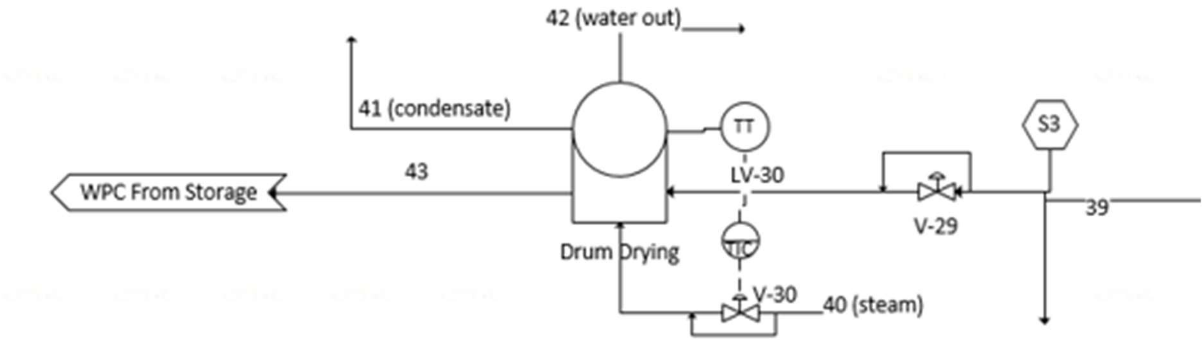


Figure 1.3: Group Drum Dryer P&ID

A mistake made by the group was the labelling in the **Figure 1.3**. In the group calculations, stream 41 is evaporated water and 42 is condensate from steam, however in the figure stream 41 is labelled condensate. Stream 42 is labelled "water out" which is the same thing as "condensate" in this case.

Figure 1.3 was used as the basis of the P&ID presented in **Section 5.1**, as well as work by Rodriguez et al. (1996).

2. Unit Design

2.1 Justification for Equipment Selection

Removal of moisture from plastic can be achieved through various technologies (British Plastics Federation, 2022; Chojnacka et al., 2021; Daud, 2003), outlined below. The selected equipment was a single drum dryer with applicator roll feed. The drum dryer was selected as it is the most universal unit procedure for this step of the process (Chalermthai et al., 2020), hence it is applicable for this use to make flakes of bioplastic. A single drum dryer was chosen over a double drum dryer as single drum dryers are good for viscous materials, double drum dryers are more suited for lower viscosities (ANDRITZSeparation, 2014). It was assumed that the polymer mixture had high viscosity due to its high solids contents, making it comparable to a slurry. A model involving 4 applicator rolls was designed, as that is standard considering the size of the dryer; the optional use of 5 or more applicator rolls is seen only with models above 14 m^2 (model E 15/30 and up) (ANDRITZSeparation, 2014). The use of applicator rolls was selected over dip feed due to the viscous nature of the plastic, as well as due to calculations performed in rigorous design (Section 2.3). The unit was designed with a vapour hood to remove evaporated water, thus avoiding excess humidity in the room, as well as associated problems such as mould.

2.1.1 Convective Dryers

2.1.1.1 Dehumidifying Dryers

In this type of dryer, air is dried through a desiccant bed, heated to a specified temperature, and fed into a hopper containing the plastic. Moisture is removed and the air becomes saturated, air is then fed though the desiccant bed to repeat the cycle (British Plastics Federation, 2022). Regeneration of desiccant is required frequently due to its limited ability to hold moisture (British Plastics Federation, 2022). Other disadvantages include the energy requirements to heat the air, multiple stages for high moisture content removal and unevenness in drying (Chojnacka et al., 2021). A similar type of dryer is the compressed air dryer, where air flow is driven by compressed air, rather than the mechanical blowers used in dehumidifying dryers (British Plastics Federation, 2022).

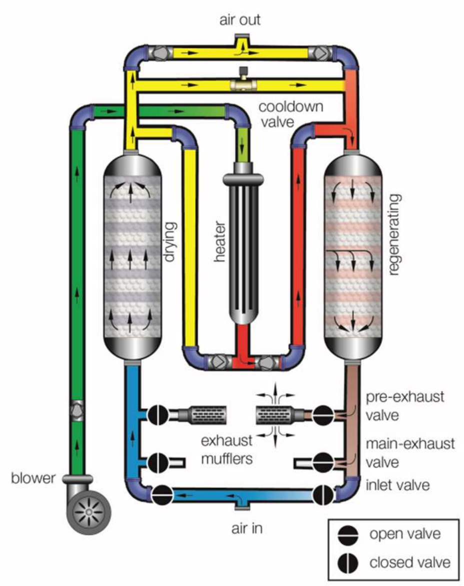


Figure 2.1: Blower Purge Desiccant Dryer. Compressed air is dried though one adsorption vessel, whilst the other is used to regenerate using dry purge air. The dry air out of the system is fed into a hopper downstream to dry the plastic (Parker, 2016)

2.1.1.2 Rotary Wheel Dryers

Energy requirement issues posed by other dryers are addressed by rotary wheel dryers, through dew point control, which prevents over drying. Some models may save up to 40% in energy consumption compared with the most efficient dehumidifying dryers, due to lower regeneration temperature. A rotating wheel is employed to continuously supply dry desiccant (British Plastics Federation, 2022). The dry air is used downstream as it is for dehumidifying dryers, moist air can be dried through the wheel, or dry air can be passed through to regenerate the desiccant.

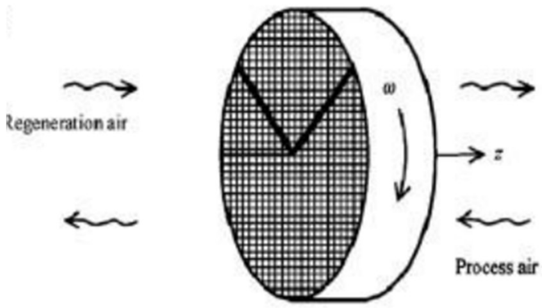


Figure 2.2: Rotary Wheel Dryer (Wang, 2015)

2.1.2 Vacuum Dryers

The boiling point of water is lowered to 56℃ through a vacuum, thus as the plastic is heated, the moisture is quickly removed (British Plastics Federation, 2022). Advantages include typical drying times 6 times faster than those for dehumidifying dryers, as well as the lack of desiccant, thus saving related expenses (British Plastics Federation, 2022).

2.1.3 Energy Field Dryers

These include infrared and dielectric dryers, which allow for short drying times and little space requirement, although may overheat the plastic, and can be expensive (British Plastics Federation, 2022).

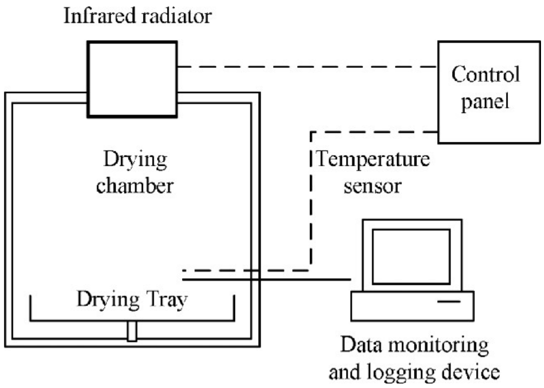


Figure 2.3: Schematic of an Infrared Dryer (Niamnuy, 2013)

2.1.4 Drum Dryers

Contact dryers involve heating of material through conduction from a hot wall. These include drum dryers and belt dryers. Disadvantages of both are greater complexity than for convective dryers, although temperature distribution is uniform, and performance and efficiency are high (Chojnacka et al., 2021). The use of superheated steam rather than air increases efficiency and heat transfer rate and reduces fire risk (Li). Dust emissions are minimal (ANDRITZSeparation, 2014).

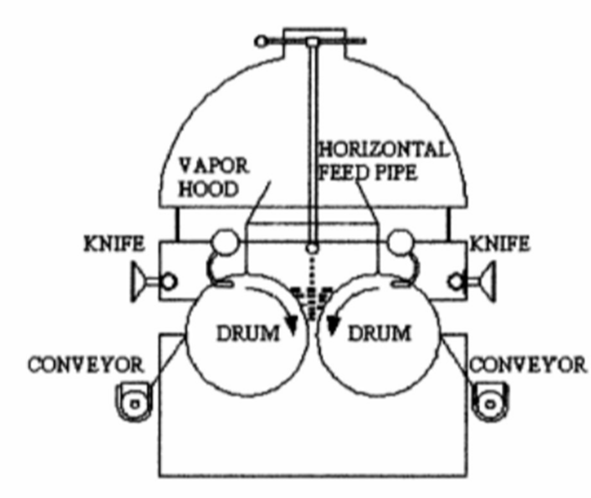


Figure 2.4: Drum Dryer Schematic (Chojnacka et al., 2021)

2.1.4.1 Single Drum Dryers

The polymer to be dried is fed to the dryer by applicator rolls, the number of which determine thickness of the plastic layer (ANDRITZSeparation, 2014). Single drum dryers are suited to “pasty or pulpy” products, the applicator rolls prevent the formation of lumps in the sheet and ensures even distribution. An alternative configuration involves a bottom dip roll, where the applicator roll lies below the drum, although this is for specific chemicals (ANDRITZSeparation, 2014) thus the standard model is preferable for the bioplastic. This is presented in **Figure 2.5 c**.

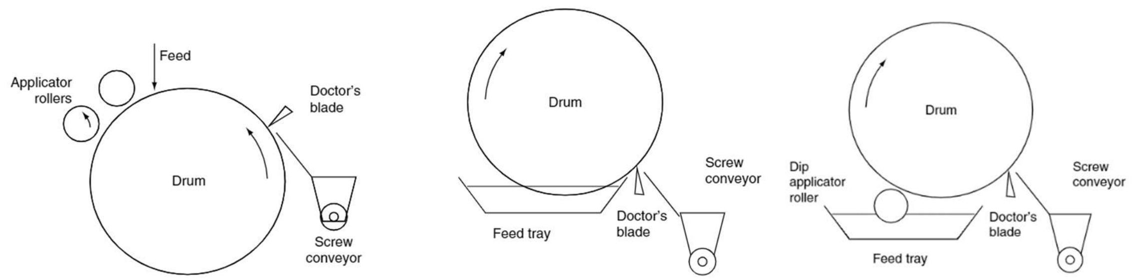


Figure 2.5: a. Single Drum Dryer with Applicator Roll Feed b. Single Drum Dryer with Dip Feed c. Single Drum Dryer with Dip Roller Feed (Daud, 2003)

2.1.4.2 Double Drum Dryers

Products with lower viscosities are suitable for use in double drum dryers. The product is fed between the two drums, which rotate in opposite directions. Layer thickness is controlled by adjusting the distance between the two drums. Applicator rolls are optional (ANDRITZSeparation, 2014). A distinction is made between double and twin drum dryers, the latter involving applicator rolls (Daud, 2003).

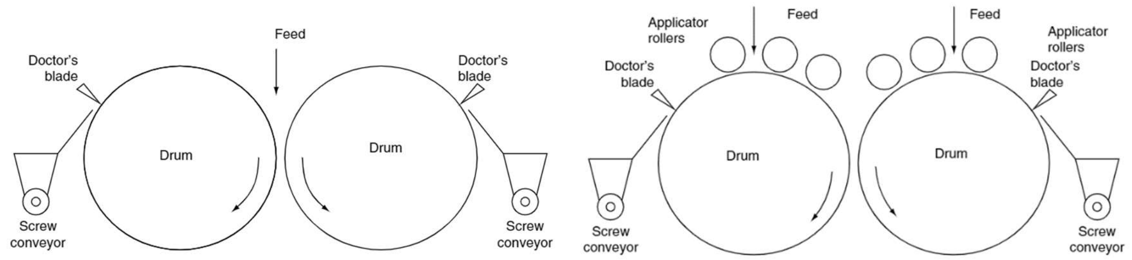


Figure 2.6: Twin Drum Dryer a. with Nip Feed b. with Applicator Roll Feed (Daud, 2003)

2.1.4.3 Vacuum Drum Dryers

Operation at low temperatures benefits heat-sensitive materials. Independence of atmospheric conditions and contamination provide uniformity in results, as well as hygiene. In the event that solvents are used, vapours can be recovered. Double drum vacuum dryers have increased production capacity compared to the single drum variant. Vacuum dryers are particularly suited to food as oxidation and protein coagulation are avoided, whilst enzymes and vitamins are preserved (ANDRITZSeparation, 2014). A similar variant is the enclosed drum dryer, which does not operate under vacuum, although as it is enclosed it is also suitable for vapour recovery or dust containment (Daud, 2003).

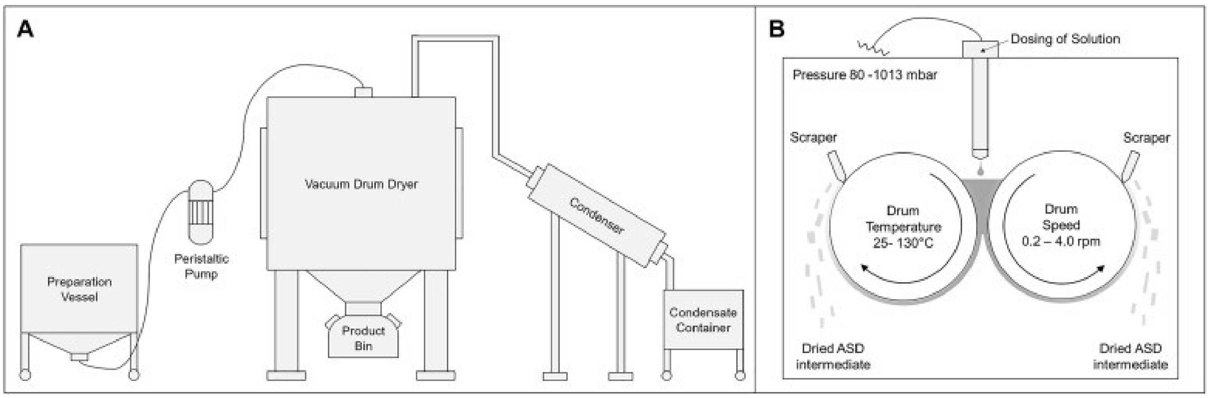


Figure 2.7: a. Vacuum Drum Dryer External View b. Vacuum Double Drum Dryer Cross-section (Schonfeld et al., 2021)

2.1.5 Spray dryers

A liquid feed is atomised within a hot drying gas, the liquid droplets are flash dried into solid particles, which are separated from the drying gas using a cyclone (Gaspar, 2014). Powder, granules, or agglomerates are achieved. As plastic flakes are required, this is undesirable, thus this option was not considered further for unit selection.

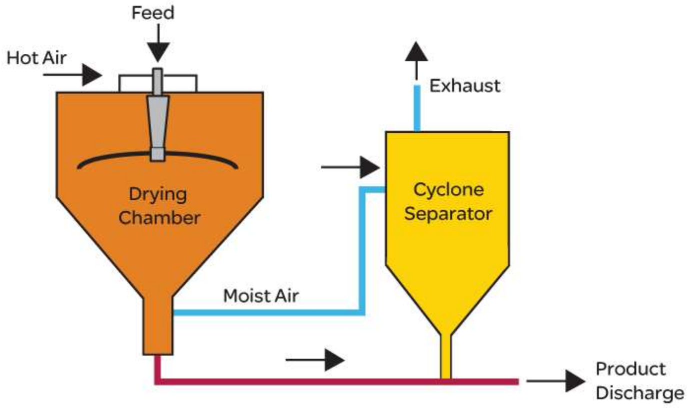


Figure 2.8: Spray Dryer (Eurotherm, 2022)

Equipment options are summarised in **Table 2.1**. Despite the negatives of the single drum dryer it was chosen for the process due to its effectiveness in drying viscous polymers.

Table 2.1: Equipment Selection Options (References: 1. British Plastics Federation, 2022; 2. Chojnacka et al., 2021; 3. ANDRITZSeparation, 2014; 4. Daud, 2003; 5. Wang, 2015; 6. Kerone, 2016; 7. Tang et al., 2003; 8. Eurotherm, 2022)

Dryer	Advantages	Disadvantages	Ref.
Dehumidifying	• Extremely low dew points can be achieved, such as -40℃	• Frequent regeneration required • Energy intensive • Multiple passes • Uneven drying • Drying speed slows as desiccant adsorbs moisture	[1,2,5]
Rotary Wheel	• Lower regeneration temperatures; up to 40% smaller energy consumption than for dehumidifying dryers • Allows for both solid and liquid dessicants – versatile	• High construction costs • Potential for air leaks	[1,5]
Vacuum	• Up to 6 times faster than dehumidifying dryer • No desiccant • Suitable for heat sensitive materials • Can operate at low temperatures	• Maintenance can be expensive • Requires skilled operators	[1,6]
Energy Field	• Short drying times • Little space required	• May over dry material	[1,
Single Drum	• Suited to viscous materials, such as the bioplastic • High energy efficiency • Easy to operate and maintain	• Lower efficiency and production rate compared to double drum dryers • Lower throughput than spray drying • High cost of changing drum surface	[3,4,7]
Double Drum	• Adjustable layer thickness • Greater efficiency and production rate than single drum dryers	• Less suited to very viscous materials	[3,4]
Vacuum Drum	• Low temperature operation • Hygienic • Vapour recovery • Suitable for dusty products, as the dust is enclosed	• Maintenance can be expensive • Requires skilled operators	[3,4,6]
Spray	• Allows for control over particle properties	• Creates powder rather than flakes	[8]

2.2 Shortcut Design

Estimates of material and energy balances, as well as dryer dimensions were obtained through shortcut design, developed during the group stage. An order of magnitude estimate of these values was required to inform the rigorous design, providing checks and guidance for iterations. Shortcut design was undertaken during the group stage due to time constraints, and the broad aspect of the project. Rigorous design is developed in section 2.3.

2.2.1 Initial Material Balances

Relevant streams and a PFD of the individual unit are presented in **Figure 2.9** and **Table 2.2**.

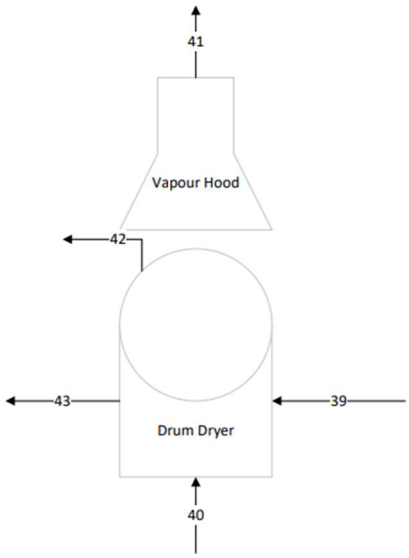


Figure 2.9: PFD of the Drum Dryer

Table 2.2: Stream Table of the Drum Dryer

Line No.	39	40	41	42	43
Stream	Centrifuged Content	Steam Inlet	Evaporated Water	Condensate Outlet	Bioplastic Product
Batch Mass Flow (tonnes)	3.81	4.230	1.295	4.230	2.515
Pressure (bar)	1.013	4.765	1.013	1.013	1.013
Temperature (Celsius)	25	150	N/A	96.43	72
Components Mass Fraction					
Water	0.4	1	1	1	0.09
Polymer and impurities	0.6	-	-	-	0.91
Total	1	1	1	1	1

Assumptions:

- Atmospheric pressure applied.
- The dryer inlet stream comprised 40% water by weight.
- 85% of water in the dryer inlet stream was evaporated.
- Mass of polymer and impurities was conserved throughout drying. Whether solids may break down due to temperature and pressure is not considered, thus fractions of solids and water may differ from reality.

In the drum dryer, 85% of the water in the centrifuged content was evaporated (Chalermthai et al., 2020). Stream 39 of the group PFD was the centrifuged content, where total flowrate:

$$F_{39} = 3.81\ tonnes\ batch^{-1}$$

The centrifuge reduced the water content of the polymer stream to 40% (Chalermthai et al., 2020). The flow of water in stream 39 was thus:

$$F_{39,water} = 0.4 \times 3.81 = 1.524\ tonne/batch$$

The remaining 2.286 tonnes per batch was the polymer and impurities.

The amount of water removed in the drum dryer was thus:

$$F_{41} = F_{39,water} \times 0.85 = 1.524 \times 0.85 = 1.295\ tonnes\ batch^{-1}$$

The amount of water in the final product was the difference between water in the centrifuged content, the inlet, and the amount of water evaporated by the dryer:

$$F_{43,water} = F_{39,water} - F_{41} = 1.524 - 1.295 = 0.2286\ tonnes\ batch^{-1}$$

As it was assumed the polymer and impurities were conserved throughout the drying process, total mass of final product was the sum of these and the water content:

$$F_{43} = F_{43,water} + F_{39,polymer\ and\ impurities} = 0.2286 + 2.286 = 2.515\ tonnes\ batch^{-1}$$

The product had a moisture content of 9%, and a solids content (polymer and impurities) of 91%. This differed from the expected moisture content of 10% (Chalermthai et al., 2020), although considering the difference is of 1% this may be due to rounding and impurities. Material balances for the steam and condensate, streams 40 and 42, are calculated in **Section 2.2.2**.

2.2.2 Initial Energy Balances

Assumptions:

- Isobaric operation at atmospheric pressure for the cold stream (the polymer/plastic).
- The plastic product was similar to PHB in terms of specific heat.
- The drum dryer was treated as a counter flow heat exchanger.
- Overall heat transfer coefficient was assumed to lie within the range for steam heating a very viscous fluid. As the plastic was mostly solid, it was treated as a slurry.
- Steam inlet temperature was 150℃.
- Condensate pressure was at atmospheric conditions.
- Streams 40 and 42 do not enter into contact with streams 39, 41 and 43, thus masses of streams 40 and 42 were equal.
- LMTD assumes no heat loss to surroundings, steady flow conditions, negligible axial conduction as well as potential and kinetic energy changes, constant specific heats and overall heat transfer coefficient (Incropera et al., 2011).

Equation 1, $Q = m\, c_p\, \Delta T$, was used, assuming negligible changes of enthalpy due to a constant pressure. Assuming the plastic had similar specific heat to PHB:

$$c_p = 1.21 + 0.0035T \quad \text{(Righetti et al., 2019)}$$

The plastic was heated from 25℃ to 72℃ (Chalermthai et al., 2020), by steam at 150℃ (Bonazzi et al., 1996). Using this temperature difference and the mass of the stream entering the drum dryer, F_{39}, the heat required was determined:

$$\mathrm{Q} = (3810kg)(72-25)K \int_{25}^{72} 1.21 + 0.0035T\, dT$$

$$\mathrm{Q} = (3810kg)(72-25)K(64.85\ kJ\ kg^{-1}\ K^{-1})$$

$$\mathrm{Q} = 1.161 \times 10^{7}\ kJ$$

For a 6-hour drying time:

$$\dot{Q} = \frac{\text{Q}}{360 \times 60\ s} = \frac{1.161 \times 10^7 [kJ]}{360 \times 60\ [s]} = 537.6\ kW$$

Steam consumption was determined from Equation 2:

$$\dot{m} = \frac{\dot{Q}}{h_{fg}} \tag{2}$$

Through extrapolating from steam tables (Beaton et al., 1989) the steam pressure was calculated as 4.765 bar. It was assumed the condensate pressure was at atmospheric conditions. The specific enthalpy of the steam was assumed 2745 kJ kg^{-1} (Beaton et al., 1989).

Therefore, the mass flowrate of steam per second:

$$\dot{m} = \frac{537.6\ [kW]}{2745\ [\text{kJ}\ kg^{-1}]} = 0.1958\ kg\ s^{-1}$$

Hence, the mass of steam per batch was determined:

$$F_{40} = 0.1958\ kg\ s^{-1} \times 360 \times 60\ s = 4230\ kg\ batch^{-1}$$

This was assumed equal to the mass of condensate out, F_{42}, as the drum dryer was treated as a heat exchanger, where cold and hot streams do not enter into contact with each other.

Using Equation 3, the Log-Mean Temperature Difference (LMTD) was determined, assuming a counter current heat exchanger. Assuming $U = 600\ W\ m^{-2}\ K^{-1}$ applied, for steam heating a very viscous fluid (Sinnott Ray K., 2009) and the area of the drum dryer of 12 m^2 (Chalermthai et al., 2020) the condensate temperature was calculated:

$$\Delta T_{lm} = \frac{\dot{Q}}{UA} \tag{3}$$

$$\Delta T_{lm} = \frac{537.6\ kW}{(0.6\ kW\ m^{-2}\ K^{-1})(12\ m^2)} = 74.67℃$$

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln\frac{(T_{h,i} - T_{c,o})}{(T_{h,o} - T_{c,i})}} \tag{4}$$

$$\Delta T_{lm} = 74.67℃ = \frac{(150℃ - 72℃) - (T_{h,o} - 25℃)}{\ln\frac{(150℃ - 72℃)}{(T_{h,o} - 25℃)}}$$

Using goal seek, $T_{h,o} = 96.43$ ℃.

Section 3 considers unit optimisation, where steam temperature is changed. For the detailed design, steam temperature used is 140℃. LMTD thus alters from the short-cut calculation, presented in **Appendix A1**. Steam outlet temperature used in design is thus $T_{h,o} = 106.8$℃.

LMTD assumes fluid specific heats are constant and that fluid temperature change is only from heat exchange; it loses its validity when a phase change occurs, such as in this case as fluid temperatures during phase change do not remain constant and cause a pressure drop (Qiao, 2018). This can be accounted for through a correction factor, although checks demonstrate difficulty applying this to the drum dryer, refer to **Section 2.3.5**.

2.2.3 Initial Sizing

Initial dimensions were based on two different drum dryer models: ANDRITZ Gouda drum dryers model E 10/30 and 15/30 (ANDRITZSeparation, 2014). The 10/30 model comprised area 9.4 m^2, whereas the 15/30 model had area 14.1 m^2. The required drum dryer area was 12 m^2, which was treated as approximately the arithmetic mean of the models' areas. Thus, dimensions were taken as approximately halfway between those of the models. The designed dryer had a diameter of 1250 mm, the average between both models, and a drum length of 3000 mm, which was the same for both models. For the rolls design, both models had 4 rolls, and the diameter was taken as 240 mm, the average between the models. A similar approach was taken to determine unit length, width, and height, as well as other dimensions such as weight. Design of the drum dryer was based on the ANDRITZ Gouda models and included a vapour hood to remove evaporated water. Refer to **Section 2.3.5** for a check on drum dryer area.

2.2.4 Justification of Initial Assumptions

The initial assumptions were justified as follows:

- The dryer inlet stream comprised 40% water by weight, and 85% of water in the dryer inlet stream was evaporated – these values were found in literature (Chalermthai et al., 2020).
- Mass of polymer and impurities was conserved throughout drying – as drum drying involved water evaporation, it was reasonable to assume all solids remained after drying.
- Isobaric operation at atmospheric pressure for the cold stream – the only deviation to atmospheric pressure is in the hot stream.
- The plastic product was similar to PHB in terms of specific heat – the plastic is described in the literature as "polyethylene-like plastic" (Chalermthai et al., 2019).
- The drum dryer was treated as a counter flow heat exchanger as the hot and cold streams move perpendicularly to each other.
- Overall heat transfer coefficient was assumed to lie within the range for steam heating a very viscous fluid. As the plastic was mostly solid, it was treated as a slurry – highly viscous. The heat transfer coefficient chosen was $U = 600\ W\ m^{-2}\ K^{-1}$, which is exactly halfway through the range ($U = 300\ to\ 900\ W\ m^{-2}\ K^{-1}$ for very viscous fluids). Condensate temperature was very near boiling point ($96.43\ ℃$) thus the assumption was deemed acceptable.
- Steam inlet temperature was 150℃ based on literature (Bonazzi et al., 1996).
- Condensate pressure was at atmospheric conditions – the pressurised steam condenses thus it is no longer pressurised.
- Streams 40 and 42 do not come into contact with streams 39, 41 and 43, thus masses of streams 40 and 42 were equal – according to ANDRITZ, the steam system is closed thus the product does not come into contact with the steam or condensate (ANDRITZ, 2022).

2.3 Rigorous Design

2.3.1 Material Balances

Assumptions made are as follows:

- Equation 5 is applicable to single drum dryers due to independence of pool height.
- Evaporation rate reduction is derived from all moisture content values from initial to final, rather than just those for the third period. This may cause inaccuracy, although as $\xi < 1$ it is assumed applicable.
- Length of periods are estimated based on a graph given by Daud (2003); this may lead to inaccuracy due to approximation.
- The plastic product is assumed similar to PHB in terms of specific heat capacity, thermal conductivity, and density. This is based on the description of the plastic as a "polyethylene-like plastic" (Chalermthai et al., 2019). The wet polymer is assumed to be of comparable density to the lowest in the range for PHB, whereas the dry plastic is assumed to be comparable to the highest in the range. This is for simplicity, although arbitrary, thus discrepancy from real values is deemed probable.
- Moisture heat capacity and thermal conductivity are assumed constant with temperature, the values used are at 50℃, approximately halfway between inlet and outlet temperatures. Greater accuracy would be achieved by varying these with temperature, although this would add complexity; as moisture heat capacity is used to calculate element heat capacity (and likewise with thermal conductivity), which changes with moisture content, it was deemed acceptable to make the simplifying assumption.
- Drum metal thickness and volume element thickness were assumed.
- Drum thermal conductivity was assumed based on Kasiri et al. (2004); precise material and whether it was similar to material in the preliminary specification sheet was not considered.
- Water density was assumed 1000 kg m^{-3}.
- Air temperature was assumed 298.2 K. This did not consider weather conditions in Somerset, nor temperature of the room.

Based on an equation to calculate moisture content of product in a double drum dryer (Vallous et al., 2002), an expression for speed of rotation of the drums was derived:

$$V = \frac{bP + M - c}{a} \tag{5}$$

where V = speed of rotation (rpm)
P = steam pressure (bar)
M = moisture content (% wet basis)
$a = 2.50 \pm 0.21$
$b = 3.28 \pm 0.38$
$c = 16.98 \pm 2.3$

MATLAB was used to evaluate speed of rotation, for three cases. In Case 1, $a = 2.50, b = 3.28, c = 16.98$. In Case 2, $a = 2.71, b = 3.66, c = 19.28$. In Case 3, $a = 2.29, b = 2.90, c = 14.68$. Results are presented in **Table 2.3**. Due to results showing little deviation, the designed speed of rotation was set to 3 rpm.

Table 2.3: Variation in Speed of Rotation depending on Values of Constants a, b, and c

Case	Speed of Rotation (rpm)
Case 1	3.0597
Case 2	2.6420
Case 3	3.5539

Equation 5 was assumed applicable to a single drum dryer as according to Vallous et al. (2002) the effect of pool level was shown to be insignificant, thus although the equation applies to nip feeding in double drum dryers it was applied to the designed single drum dryer due to independence of pool height. Speeds of rotation calculated were reasonable, similar to those calculated by Vallous et al. (2002) and within the range given by e-Krishi Shiksha (2012), thus this assumption was deemed appropriate. An equation for exit mass flowrate as a function of pool height was deemed unapplicable, as calculating pool height using flow of stream 43 gave results two orders of magnitude too large, compared to values presented by Vallous et al. (2002). Thus, for the designed drum dryer nip feeding is not an option as it involves a pool, thus roll feeding was selected. According to Tang et al. (2003) it is applicable to both single or double drums and viscous materials.

A material balance on an element of polymer drying on the drum surface was performed, based on work by Kasiri et al. (2004), this was solved alongside an energy balance. The material balance considered moisture content of the element, whereas the energy balance considered temperature of the element. Second-order differential equations were solved using MATLAB. The derivation of the centred finite difference approach is detailed in **Appendix A2**. The volume element comprised width $Rd\theta$, thickness d, and length L.

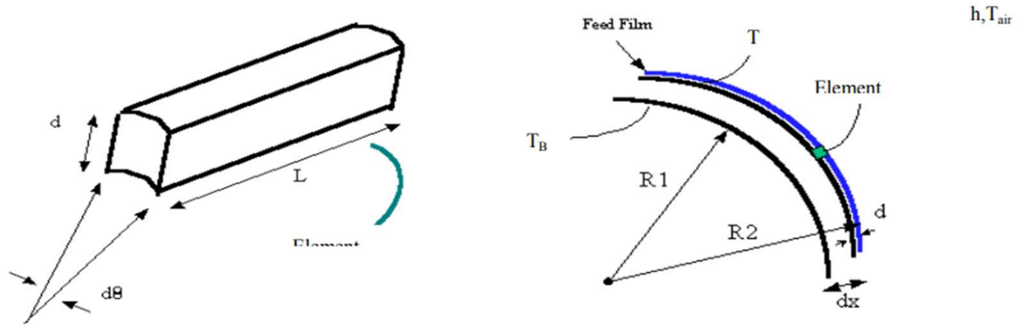


Figure 2.10: a. Element Volume of Plastic b. Cross-Section of Drum and Element (Kasiri et al., 2004)

The material balance equation comprised three terms. The first term regards net mass entering the element due to moisture concentration gradient. Equations are taken from Kasiri et al. (2004).

$$W_\theta - W_{\theta+d\theta} = \frac{D_{we} L d \alpha \rho}{R_2} \frac{\partial^2 X}{\partial \theta^2} \quad (6)$$

Net mass leaving the element is due to moisture evaporation:

$$W_E = \frac{M}{1000} K_G R_2 L (P^{sat} - P_w)$$

Mass transfer rate is given by:

$$MTR = K_G(P^{sat} - P_w)$$

$$W_E = \frac{M}{1000} R_2 L \times MTR \quad (7)$$

The drying of the plastic on the drum can be regarded in three periods. In the first period, the initial application zone, the sudden exposure of the feed to the hot drum surface causes rapid boiling and removal of most of the moisture (Daud, 2003). Drum surface temperature drops as a result. The second period is the initial sheet zone, where water boils as drum surface drops and sheet temperature remains constant (Daud, 2003). The third period is the slow drying zone, where the sheet quickly dries and temperatures of both the sheet and the drum surface rise, caused by the reduction in boiling (Daud, 2003). Evaporation rate reduction during the third drying period is considered with a factor ξ. During the third period, after critical moisture content is exceeded, a four-order polynomial given by Kasiri et al. (2004) was used to model the curve of evaporation rate as a function of moisture content of the product.

$$E_v = 3.9098X^4 - 6.1117X^3 + 2.6640X^2 + 0.6828X$$

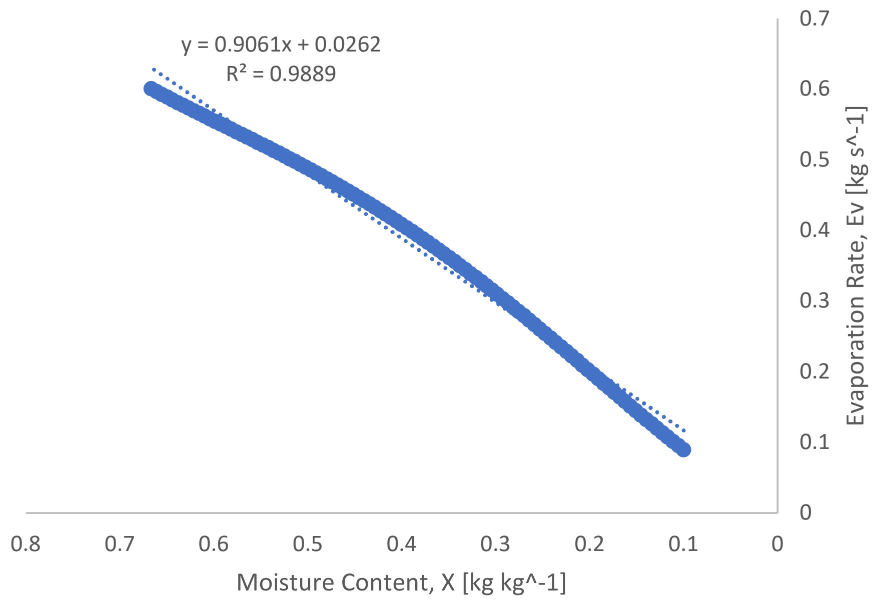


Figure 2.11: Evaporation Rate during the Third Drying Period, as a function of Moisture Content

Modelling a line of best fit to the curve gave a gradient of 0.9061, which was used as a value for ξ during the third period. As the exact moisture content values were unknown, as well as at what values each period occurred, equally spaced values from initial to final moisture content were used. Therefore, the gradient is inaccurate, although gives a ballpark estimate. During the third period, $\xi < 1$, thus $\xi = 0.9061$ is applicable.

The transient mass balance is derived from Equations 6 and 7.

$$\frac{D_{we} L d \alpha \rho}{R_2} \frac{\partial^2 X}{\partial \theta^2} - \frac{M}{1000} R_2 L \xi \times MTR = L d R_2 \alpha \rho_s \frac{\partial X}{\partial t}$$

Time dependency can be replaced with the following:

$$\frac{\partial X}{\partial t} = \frac{\partial X}{\partial \theta} 2\pi V_{rc}$$

Therefore, the material balance model is given by:

$$\frac{D_{we} L d \alpha \rho}{R_2} \frac{\partial^2 X}{\partial \theta^2} - \frac{M}{1000} R_2 L \xi \times MTR = 2\pi V_{rc} L d R_2 \alpha \rho_s \frac{\partial X}{\partial \theta} \quad (8)$$

This was solved in MATLAB using finite difference equations. The central difference approach was selected for its low error, compared to forward Euler. Further details are provided in **Section 2.3.6**, and derivations are in **Appendix A2**.

Initial moisture content was calculated from the ratio of water to solids in the inlet stream to the drum, Stream 39:

$$X_i = \frac{F_{39,water}}{F_{39,polymer\ and\ impurities}} = \frac{1524kg}{2286kg} = 0.6667kg_{moisture}\ kg_{dry\ solid}{}^{-1}$$

Similarly, final moisture content was calculated from the ratio of water to solids in the outlet, Stream 43:

$$F_{39,polymer\ and\ impurities} = F_{43,polymer\ and\ impurities} = 2286kg$$
$$X_f = \frac{F_{43,water}}{F_{43,polymer\ and\ impurities}} = \frac{228.6kg}{2286kg} = 0.1kg_{moisture}\ kg_{dry\ solid}{}^{-1}$$

Three-quarters of a turn of the drum are required from feed to removal of the plastic (Kasiri et al., 2004), thus distance in radians can be calculated, knowing that there are 2π radians in a circle:

$$2 \times \frac{3}{4}\pi rad = 4.712rad$$

From Daud (2003), Period 1 lasts from 0 to around 0.3 rad, Period 2 from 0.3 to 1.7 rad and Period 3 from 1.7 to around 4.5 rad – assumed 4.712. This equates to lengths of 0.1875, 0.875 and 1.883 m, respectively. Thus, proportions of each were calculated relative to total length, to calculate how many points in MATLAB were in each period. This was used in 'for' loops to change values, such as ξ or drum surface temperature.

Values used in the MATLAB code are as follows:

Table 2.4: MATLAB Variables (References: 1. Kasiri et al., 2004; 2. Omnexus, 2022; 3. PubChem, 2022; 4. Polymerdatabase.com, 2022; 5. Engineering ToolBox, 2004; 6. Bucci et al., 2016; 7. Engineering ToolBox, 2018; 8. Daud, 2003; 9. Kanevce et al., 2003)

Symbol	Variable	Value	Units	Justification
C_ps	Plastic heat capacity	118	J mol^{-1} K^{-1}	Assuming plastic is similar to PHB [4]
C_pw	Moisture heat capacity	75.33	J mol^{-1} K^{-1}	Assuming constant with temperature, value at 50℃ (approximately between 25 and 72℃) [5]
D	Drum diameter	1.25	m	Group Design specification sheet (cf. **Unit Design Brief**)
Delta_x	Drum metal thickness	0.008	m	Assumption
D_we	Moisture diffusivity in element	1.657E-9	m^2 s^{-1}	Average based on equations [9] (cf. **Appendix A3**)
d_0	Volume element thickness	0.001	m	Assumption
k_d	Drum thermal conductivity	35	W m^{-1} K^{-1}	Assumption [1]
k_s	Plastic thermal conductivity	0.419	W m^{-1} K^{-1}	Assuming plastic is similar to PHB [6]
k_w	Moisture thermal conductivity	0.6406	W m^{-1} K^{-1}	Assumption, at 50℃ [7]
L	Drum length	3	m	Group Design specification sheet (cf. **Unit Design Brief**)
M	Moisture molecular weight	18.02	g mol^{-1}	[3]
Rho_f	Feed density	1300	kg m^{-3}	Assuming the wet polymer has a density comparable to the lowest PHB density, due to the presence of water [2]
Rho_s	Solid density	1500	kg m^{-3}	Assuming the polymer has a density comparable to the highest PHB density as it is dry [2]
Rho_w	Water density	1000	kg m^{-3}	Assumption
R_2	Drum outer radius	0.625	m	Group Design specification sheet (cf. **Unit Design Brief**)
T_air	Air temperature	298.2	K	Assumption
T_B0	Initial internal surface temperature of cylinder	403.2	K	Based on graph presented by [8]
V	Drum speed	0.05	s^{-1}	3 rpm

Figure 2.12 presents the Material Balances for moisture content in the volume element, as the drum rotates.

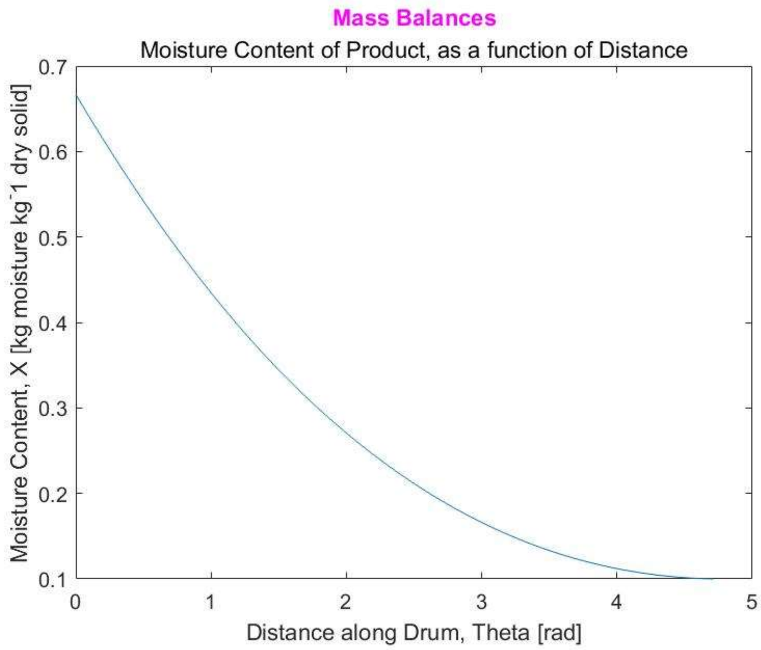


Figure 2.12: Material Balance Results

This differs from the curve given in literature (Kasiri et al., 2004):

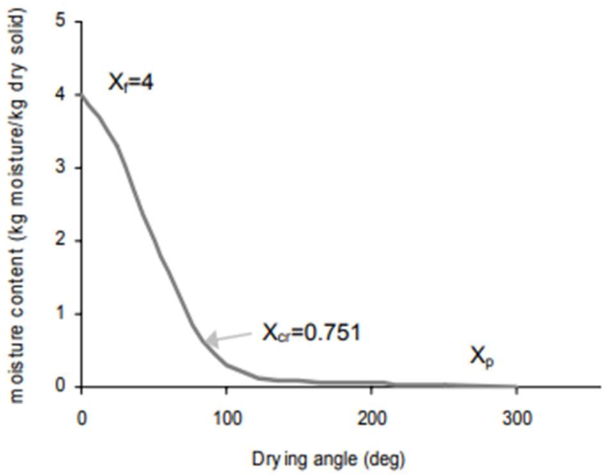


Figure 2.13: Material Balance Curve (Kasiri et al., 2004)

During the first period, moisture content decreases at a lower rate than during the second period. This is not seen in the model, where the gradient remains constant during these two periods. The reduction of rate of moisture evaporation seen in the third period is present in the model, although not to the extent demonstrated in **Figure 2.13**. As the sheet dries, rate of evaporation decreases, as there is less moisture to evaporate. As the ratio for this used in the model is near 1, $\xi = 0.9061$, this may explain the less pronounced decrease in rate. In the first two periods, $\xi = 1$, thus the rate remaining the same in both is expected. Thus, it is concluded that a lower rate in the first period is due to another factor that is seen in the real case, and not in the model. Values for ξ could be investigated further to increase the accuracy of the model. A value for $\xi < 1$ during the first period could represent the lower evaporation rate demonstrated in the real case. The evaporation rate increase during the first period is due to the gradual heating of the feed temperature (Kasiri et al., 2004), thus $\xi \rightarrow 1$ could represent this. Thus, the model was modified to vary ξ during the first period. Initially, values from 0.9

to 1 were chosen, although this did not return the desired results. Various values tending to 1 were attempted, although the slope did not change as desired, instead, the temperature peak during the first period of the energy balances increased as initial ξ was decreased. Thus, the lower evaporation rate during the first period cannot be modelled by lowering ξ, as this ratio does not represent the first period. During the third period, increasing ξ was found to produce a more similar graph to the real case, contrary to expectation. This is likely due to error in the model, as with $\xi = 1$ moisture content as low as 0.0994 was attained, before rising to the final value of 0.1.

2.3.2 Energy Balances

Assumptions:

- Heat transfer is assumed through forced convection, due to the speed of drum rotation. This determines the correlation used for Nusselt number, thus the convective heat transfer coefficient for air calculated.
- Values were calculated at drum surface temperature, approximated as between 125 and 130℃.
- Atmospheric pressure applies, which affects mass transfer rate of moisture evaporation.
- 140℃ steam is used as the heating fluid, based on Daud (2003). This differs from the 150℃ steam used in Group Design; this is discussed in **Section 3**.

The energy balance model is given by:

$$\frac{kLd}{R_2}\frac{\partial^2 T}{\partial \theta^2} + k_d R_1 L \frac{T_B - T}{\Delta x} - hR_2 L(T - T_{air}) - \frac{M}{1000} R_2 L \xi C_{pw} T \times MTR = 2\pi V_{rc} C_p L d R_2 \rho \frac{\partial T}{\partial \theta} \qquad (9)$$

The first term is the net energy entering the element by conduction heat transfer from θ to $\theta + d\theta$. The second term is the energy entering by conduction from θ to $R_1 + dx$. The third term is the heat leaving by convection.

Drum internal radius was calculated as follows:

$$R_1 = R_2 - d - \Delta x$$

Variation of element thickness is given by:

$$d = d_0 \frac{\rho_f - \rho_w}{\rho - \rho_w}$$

Element thickness is constant during the third drying period.
Weight average element density is given by:

$$\rho = \frac{\rho_s(1 + X)}{1 + (X\rho_s/\rho_w)}$$

Element heat capacity varies widely due to change in moisture content:

$$C_p = \frac{C_{ps} + C_{pw}X}{1 + X}$$

Element thermal conductivity:

$$k = \frac{k_s + k_w X}{1 + X}$$

Element solid content is given by:

$$\alpha = \frac{1/\rho_s}{\frac{1}{\rho_s} + \frac{X}{\rho_w}}$$

Heat transfer is assumed through forced convection, due to the speed of drum rotation (Kasiri et al., 2004). Air convective heat transfer coefficient was evaluated from the following:

$Nu = 0.664 Re^{0.5} Pr^{0.33}$ (Engineers Edge, 2022)

From Engineering ToolBox (2003;2004;2009) at temperatures between 125 and 130℃, as values are taken at drum surface temperature:

$$Pr = \frac{C_{p,air}\mu_{air}}{k_{air}} = \frac{(1014Jkg^{-1}K^{-1})(19.73 \times 10^{-6}Nsm^{-2})}{(0.03333Wm^{-1}K^{-1})} = 0.6002$$

Density of air at 130℃ is taken from Engineering ToolBox (2003). Velocity of air passing over drum is given by Kasiri et al. (2004).

$$Re = \frac{\rho_{air}u_{air}D}{\mu_{air}} = \frac{(1.078kgm^{-3})(0.25ms^{-1})(1.25m)}{(19.73 \times 10^{-6}Nsm^{-2})} = 17{,}070$$

$$Nu = 73.30$$

$$h = \frac{Nu \times k_{air}}{D} = \frac{(73.3)(0.03333Wm^{-1}K^{-1})}{(1.25m)} = 1.954Wm^{-2}K^{-1}$$

Assuming a pressure of 1 atm, from Kasiri et al. (2004), see **Appendix A4**:

$$K_G = \frac{0.281Re^{0.4}G_m}{PSc^{0.56}}$$

$$G_m = c_{air}u_{air} = (41.67mol\,m^{-3})(0.25ms^{-1}) = 10.42mol\,m^{-2}s^{-1}$$

Moisture diffusivity in air is taken from Engineering ToolBox (2018)

:

$$Sc = \frac{\mu_{air}}{\rho_{air}D_{w,air}} = \frac{(19.73 \times 10^{-6}Nsm^{-2})}{(1.078kgm^{-3})(0.5 \times 10^{-4}m^2s^{-1})} = 0.3660$$

$$K_G = 253.5mol\,atm^{-1}m^{-2}s^{-1}$$

Saturation pressure of water at 130℃ is taken from Engineering ToolBox (2004), moisture partial pressure in air is taken from Engineering ToolBox (2004):

$$MTR = K_G(P^{sat} - P_w) = 253.5mol\,atm^{-1}m^{-2}s^{-1} \times (2.67 - 0.01974)atm = 671.8mol\,m^{-2}s^{-1}$$

Figure 2.14 presents the Energy Balances for temperature of the volume element, as the drum rotates.

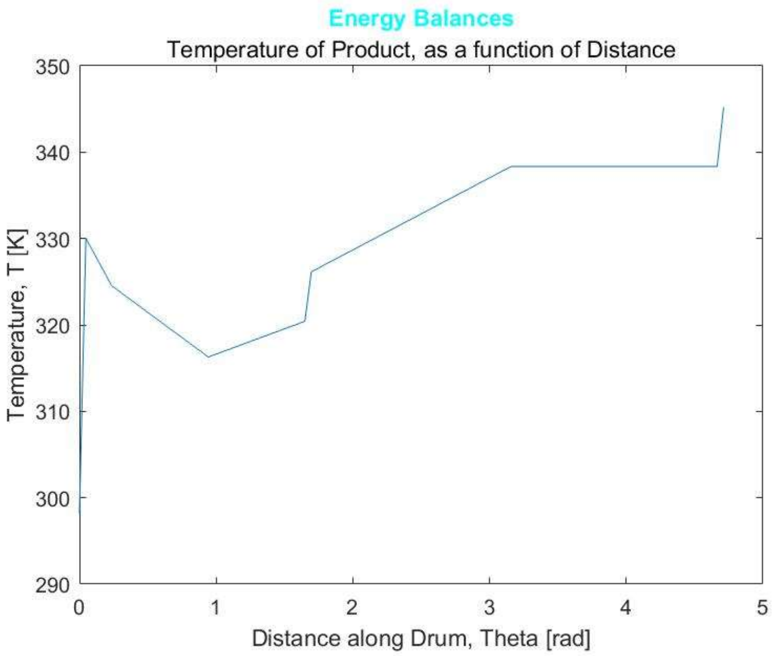


Figure 2.14: Energy Balance Results

This differs from the curve given in literature (Kasiri et al., 2004), although the three periods are recognizable, and assumptions made in model development may be the cause of inaccuracies in results.

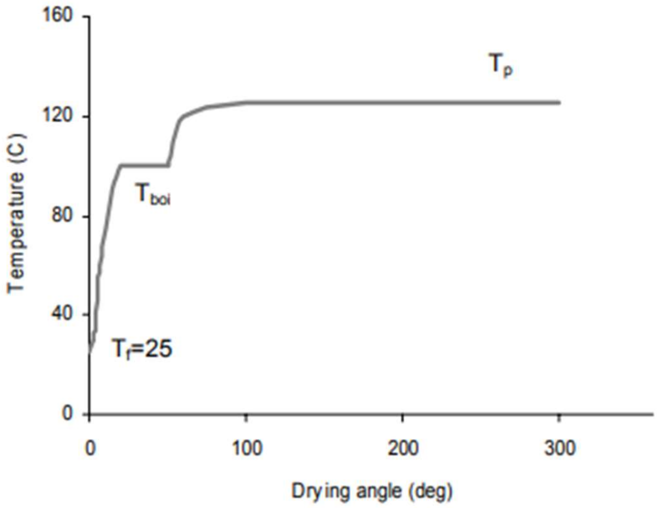


Figure 2.15: Energy Balance Curve (Kasiri et al., 2004)

During the first period, temperature increase in the model is sudden, jumping from 298.2K to 330.0K, then decreasing to 324.5K. The decrease in temperature is due to the decrease in drum surface temperature modelled, from 130 to 120℃ in the first period. The second period is split into two halves, the first where temperature continues to decrease, albeit at a greater rate, causing decrease in element temperature to reflect this, reaching 316.3K. The latter half of the second period involves temperature increase of the element to 320.4K. The third period is also split into two halves, the first involving a temperature increase following a jump of almost 6K. This jump suggests an error in the model. The second half of the period involves a temperature plateau at 338.3K. Final temperature of 345.2K is therefore only reached after a jump. Thus, according to the model, final plastic temperature would be around 65℃, rather than the expected 72℃. Element temperature reflects drum surface temperature in the model. In reality, although drum surface temperature dips, element temperature does not mirror this. From the literature, period 2 should be at constant temperature as phase change occurs, it is at boiling temperature, although since final bioplastic temperature is below this then it may not be applicable. Despite this, the fluctuations in temperature do not appear reasonable. This presents limitations in the model. If it is to be assumed that the model is suitable, however, parameters must be altered to achieve the target outlet temperature. Decreasing drum metal thickness to 6 mm gives a temperature plateau above the required temperature, at around 79.5℃. 7 mm thickness gives this temperature 0.164K above the required final temperature; as temperatures closer to 345.2K are only achieved from levels of accuracy that would be inappropriate for drum thickness considering the model, 7 mm was chosen. Compared to the original case of 8 mm thickness, the 7 mm case involves temperatures during each period of around 7K higher. Specific metal was chosen for detailed design (see **Section 4.1**). From literature, a viable combination is AISI 4140 coated with chromium for the drum (Onduk et al., 2009). Thermal conductivity of the former is 42.6 W m^{-1} K^{-1} (AzoMaterials, 2019); assuming chromium layer is thin, thus has no appreciable effect on heat capacity, the model's value for drum heat capacity can be updated. Temperature plateaus at around 81.5℃. Changing drum metal thickness again gives 8.5 mm and plateau at 345.36K. Thus, based off the model, detailed design includes an updated drum metal thickness of 8.5 mm.

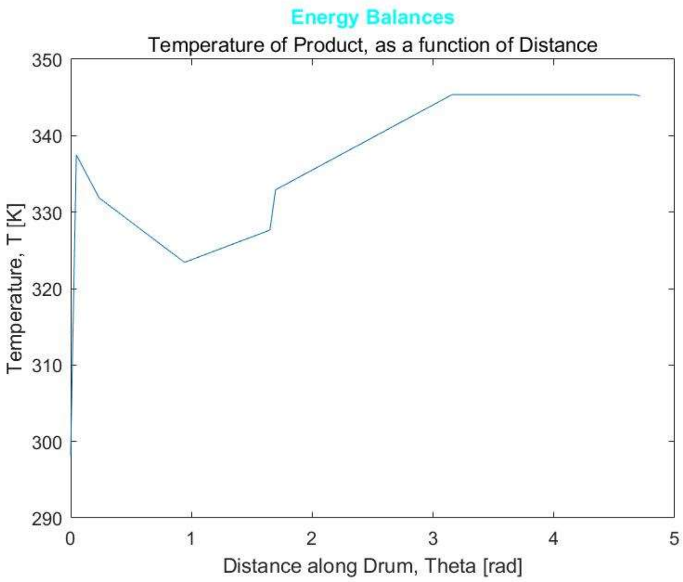


Figure 2.16: Energy Balance Curve for 8.5 mm Thick Drum Metal

Another potential issue with the model is the fact that element thickness was greater than initial element thickness for the first 30 points, where it was 0.0012 and 0.0011 m. Initial thickness was 0.001 m. Changing this initial value did not solve the issue. This variation is due to changing element density, this discrepancy appears to be a problem with the equations developed by Kasiri et al. (2004).

2.3.3 Pressure Drop and Losses

Assumptions:

- Pressure drop calculations pertaining to heat exchangers are applicable to the drum dryer, which may incur error as a drum dryer differs from a shell-and-tube heat exchanger, although they were deemed comparable.
- Steam outlet temperature was determined as 106.8℃ based on the LMTD method, calculated in **Appendix A1**. This value differs from that in the Group Design, as inlet steam temperature is different. It is assumed that steam exits the dryer, rather than condensate mentioned in literature (ANDRITZSeparation, 2014). It differs also from values given in **Section 2.3.5**; drum dryer area is $12m^2$, rather than $11.78m^2$ from checks.

It is assumed that pressure drop calculations pertaining to heat exchangers are applicable to the drum dryer, where the plastic on the outside of the cylinder is treated as a cooling fluid, and the steam as the stream to be cooled. Steam temperatures used were 140 and 106.8℃ for inlet and outlet, respectively. Calculations are taken from Sieder and Tate (1936). Properties are taken at 123.4℃, which is the mean of the inlet and outlet temperatures, and 130℃, the wall temperature. These values were extrapolated from steam tables (Beaton, 1986).

$$G = \frac{4230kg}{6 \times 60 \times 60s} \times \frac{1}{\pi(0.625m)^2} = 0.1596kg\ m^{-2}s^{-1}$$

$$\frac{DG}{\mu_{steam,123.4℃}} = \frac{(1.25m)(0.1596kg\ m^{-2}s^{-1})}{13.17 \times 10^{-6}kg\ m^{-1}s^{-1}} = 15{,}150$$

From **Figure 2.17**, $f \times \phi = 0.08$

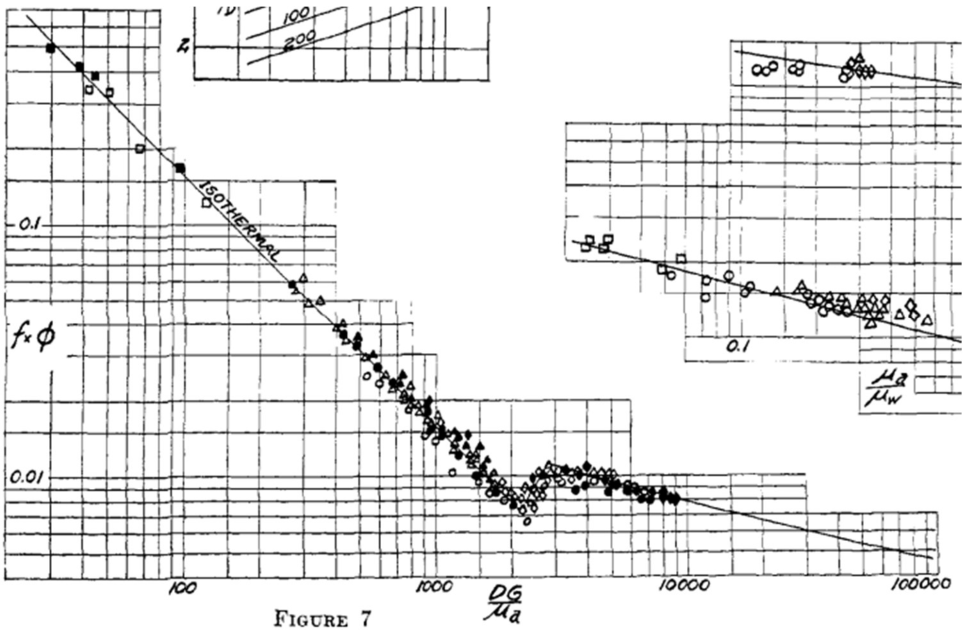


Figure 2.17: Friction Factor inside Heat Exchanger Tubes Correlation (pictured bottom left) (Sieder and Tate, 1936)

$$\phi = 1.02\left(\frac{\mu_{123.4℃}}{\mu_{130℃}}\right)^{0.14} \ for \ \frac{DG}{\mu} > 2100 \tag{10}$$

$$\phi = 1.02\left(\frac{13.17 \times 10^{-6} kg\ m^{-1}s^{-1}}{13.43 \times 10^{-6} kg\ m^{-1}s^{-1}}\right)^{0.14} = 1.017$$

$$f = 0.07866$$

$$\Delta h = 2f\frac{u^2 L}{gD} = 2f\frac{\left(\frac{G}{\rho_{steam,130℃}}\right)^2 L}{gD} = 2(0.07866)\frac{\left(\frac{0.1596kg\ m^{-2}s^{-1}}{0.5432kg\ m^{-3}}\right)^2 (3m)}{(9.81m\ s^{-2})(1.25m)} = 3.322 \times 10^{-3}m \tag{11}$$

$$\Delta P_{loss} = \Delta h \rho g = 0.01770Pa$$

Thus, pressure losses inside the drum dryer are 0.01770 Pa. To check relevancy of this result:

From steam tables, $P_i = 3.612bar$, $P_o = 1.289bar$; $\Delta P = 3.612 - 1.289 = 2.323bar$

$$\Delta P + \Delta P_{loss} = 232{,}300.0177Pa \approx 232{,}300Pa$$

Thus, pressure losses are negligible compared to pressure drop over the drum.

2.3.4 Design Procedures and Codes

The two codes and standards that apply to pressure vessels in the UK are BS 5500:1997 and ASME VIII (ASME Boiler and pressure vessel code:1998) (Health and Safety Executive, 2022). These both require inspection from an independent authority during design and construction. Factors that require consideration in unit design are as follows (Health and Safety Executive, 2022):

- Internal and external static and dynamic pressures
Steam pressure for 140℃ steam is 3.612 bar. All other pressures are 1 atm. Due to elevated pressures inside the drum, pressure safety systems are required.

- Ambient and operational temperatures
Steam temperatures between 120 and 190℃ are usually used in drum dryers (ANDRITZ, 2022); materials must thus be suited to these temperatures. Material selection is presented in **Section 4.1**. Maximum service temperature of AISI 4140 is around 630℃; minimum service temperature is around -60℃ (EduPack, 2009). Maximum service temperature of chromium is around 440℃; there is no minimum (thus -273℃) (EduPack, 2009). Maximum service temperature of AISI M7 is around

555℃; minimum is around -63℃ (EduPack, 2009). Lowest operating temperatures are at room temperature, thus the materials chosen are suitable. Higher steam temperatures are investigated in **Section 3.1.2**; however, material strength decreases with temperature (Health and Safety Executive, 2022), thus lower steam temperatures are preferable. Further material selection criteria regarding codes and standards are presented in **Section 4.4**.

- Weight of vessel and contents:

Weight calculations are presented in **Section 4.2**. The contents of the drum are steam and condensate on the inside, and plastic on the outside.

- Stress:

Pressure and wall thickness of the drum are investigated, and checks performed, in **Section 2.3.5**.

- Reaction forces and moments from attachments or piping:

It is assumed that moments are negligible for the unit.

- Fatigue, corrosion/erosion, creep and buckling:

Effects relating to these are presented in **Section 4.3**.

Pressure vessels, such as the drum dryer, are prone to failures if certain design features are not considered thoroughly (Health and Safety Executive, 2022):

- Discontinuities, such as at the ends of the drum.
- Joints.
- Holes and openings.
- Flanges.
- Nozzles and connections.
- Bolt seating and tightening.
- Supports and lugs.

Other factors to be considered include regular examination inside the drum by an access opening, a way to drain and vent the vessel, and a way to empty the drum. It must be demonstrated that correct materials have been used, as well as appropriate construction techniques. Equipment must be of the correct material, with the correct treatment, and installed as specified by the design schedule. Documents demonstrating checks performed during construction were adequately supervised are required (Health and Safety Executive, 2022). Equipment requires commissioning; records must be kept of this. Completion and hand over certificates are required. Evidence of mechanical completion checks is also required, as well as cleaning and pressure testing. Witnesses are required for performance tests and inspection. Checks must verify equipment installation according to engineering drawings and P&IDs, as well as conformity to codes and standards. Noise and vibration checks are required for the drum. Records of any modifications made must be kept, as well as reviews of safety and environmental impact (Health and Safety Executive, 2022).

Pre-commissioning and commissioning checks may include (Health and Safety Executive, 2022):

- Pre-commissioning HAZOP.
- Checks equipment agrees with PFDs and engineering diagrams.
- Electrical, mechanical, civil installation checks; examples include drum rotation and piping checks.
- Safety system and instrumentation and control checks; set point verifications, alarm testing.
- Commissioning tests using process materials.

Other standards for pressure vessels include EN 13445, PED 2014/68/EU, ASME VIII-1, and AD 2000-Merblatt (GPI-Tanks, 2021). For the doctor knife and plastic product, EC1935/2004 applies (European Parliament, 2016).

2.3.5 Checks and Comparison of Results

The drum dryer is compared to a heat exchanger in design. However, the application of correction factor proved this assumption is weak. Ratio of hot and cold streams is used in charts to determine correction factor, although the drum dryer's ratio is too large for the chart values.

$$P_{LMTD} = \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{h,o}} = \frac{72℃ - 25℃}{140℃ - 106.8℃} = 1.416$$

$$P_{LMTD} > 1$$

Throughout the report the drum dryer is treated as a type of heat exchanger, although this comparison may skew results.

Drum drying surface area calculation was neglected in the Group Report, it was assumed $12m^2$ based on rough estimates. Detailed design of the unit thus necessitates greater accuracy:

$$A = \pi(1.25m)(3m) = 11.78m^2$$

This affects LMTD calculations, thus steam outlet temperature.

$$\Delta T_{lm} = \frac{537.6\ kW}{(0.6\ kW\ m^{-2}\ K^{-1})(11.78\ m^2)} = 76.06℃$$

$$\Delta T_{lm} = 76.06℃ = \frac{(140℃ - 72℃) - (T_{h,o} - 25℃)}{\ln\frac{(140℃ - 72℃)}{(T_{h,o} - 25℃)}}$$

Using goal seek, $T_{h,o} = 109.7$ ℃. This differs from the temperature used in design. Overall heat transfer coefficient also varies, during the initial application zone it is between 2000 and $7000Wm^{-2}K^{-1}$, and during the initial sheet zone it is between 600 and $1250Wm^{-2}K^{-1}$ (Daud, 2003). The short-cut design value of $600Wm^{-2}K^{-1}$ was the lowest in the range, thus it may not represent all periods with sufficient accuracy.

$$\Delta T_{lm} = \frac{537.6\ kW}{(1.25\ kW\ m^{-2}\ K^{-1})(11.78\ m^2)} = 36.51℃$$

Using goal seek, $T_{h,o} = 41.67$ ℃. Thus, the range of outlet steam or condensate temperatures varies widely depending on overall heat transfer coefficient. This value is assumed in this design since it is usually determined through experiment. Due to uncertainty in the exact value, an outlet of 106.8℃ is assumed for rigorous design.

Calculations regarding checks on whether the designed vessel can withstand operating pressure are as follows:

Assumptions:

- The drum is seamless, $E = 1$. However, if drum construction requires welding, then this assumption is invalid, and $E = 0.85$ (Raheja, 2019).
- $S = 10{,}000$ or more for the material used in the drum wall.

To check whether wall thickness of the vessel was adequate, various equations were used, with varying results. It was concluded that the 8.5 mm drum wall was sufficient to withstand operating pressure. A relation for required thickness of a thin-walled vessel was taken from Raheja (2019). S values were based on Engineers Edge (2022), where S is maximum allowable stress according to ASME Section II. All values for S are greater than 10,000 psi in the table presented, thus a value of 10,000 is used. E is welding factor; for a seamless pipe this is 1, it was assumed the drum was seamless.

$$t_c = \frac{PR_1}{SE - 0.6P} \text{ if } P \leq 0.385SE \tag{12}$$

$52.39psi < 3850psi$ thus, it is applicable

$$t_c = \frac{(3.612bar)(0.6165m)}{(10{,}000psi) - 0.6(3.612bar)} = \frac{(52.39psi)(24.27inch)}{(10{,}000psi) - 0.6(52.39psi)} = 0.1276inch = 3.241mm$$

$t_c < 8.5mm$, thus, the designed thickness can withstand the pressure.

If the drum is welded, $E = 0.85$, thus:

$$t_c = \frac{(52.39psi)(24.27inch)}{(10{,}000psi)(0.85) - 0.6(52.39psi)} = 0.1501inch = 3.813mm$$

Thickness of the drum wall can thus withstand the pressure even if it is welded.

However, as presented in **Appendix A5**, other calculations demonstrated that the thickness of the wall was insufficient. Thicknesses required were calculated as $8.57mm$ and $33.45mm$. In the former case, this value was used in the material and energy balance MATLAB script, where target plastic outlet temperature of 72℃ was reached. In the latter case, however, the outlet temperature was -34℃. To reach 72℃, a drum surface temperature of 308℃, thus even hotter steam, was required. Due to these results, it was assumed the calculations that gave $33.45mm$ thickness were incorrect. As the value for S that gave thickness $8.57mm$ was much smaller than the values given by Engineers Edge (2022), it was assumed that this minimum thickness was also incorrect, thus the minimum thickness of $3.241mm$ was chosen.

2.3.6 Algorithms and Progressions in Complexity

The centred finite difference approach was used to derive matrices for use in MATLAB, presented in **Appendix A2**. Second-order partial differential equations were solved for moisture content and temperature of the plastic. Spatial discretisation was performed, over N points, giving a total of $N + 1$ points. The value of $N = 100$, this was chosen arbitrarily. Length of the drum used, "ThetaLength" was in radians.

```
N = 100;       % arbitrary no. of points
dTheta = ThetaLength/N;
Theta = [0,dTheta*[1:N]]; % vector of discretised points
```

Moisture content was also discretised over N points. A 'for' loop, given in **Appendix A6** was used for changing volume element thickness, evaporation rate ratio, and surface temperature, for each of the three drying periods. The length of each period was determined as a number of points; if the iteration of "j" were in that period then the appropriate equations would apply. **Appendix A7** presents the algorithm used to model the derived matrices for material balances. The final MATLAB script resulted from progressing in complexity; initial iterations involved many variables being assumed constant, to develop a functioning script, before making the necessary adjustments to model various variables. The flowchart presented in **Figure 2.18** details the steps taken in creating the MATLAB code and achieving results

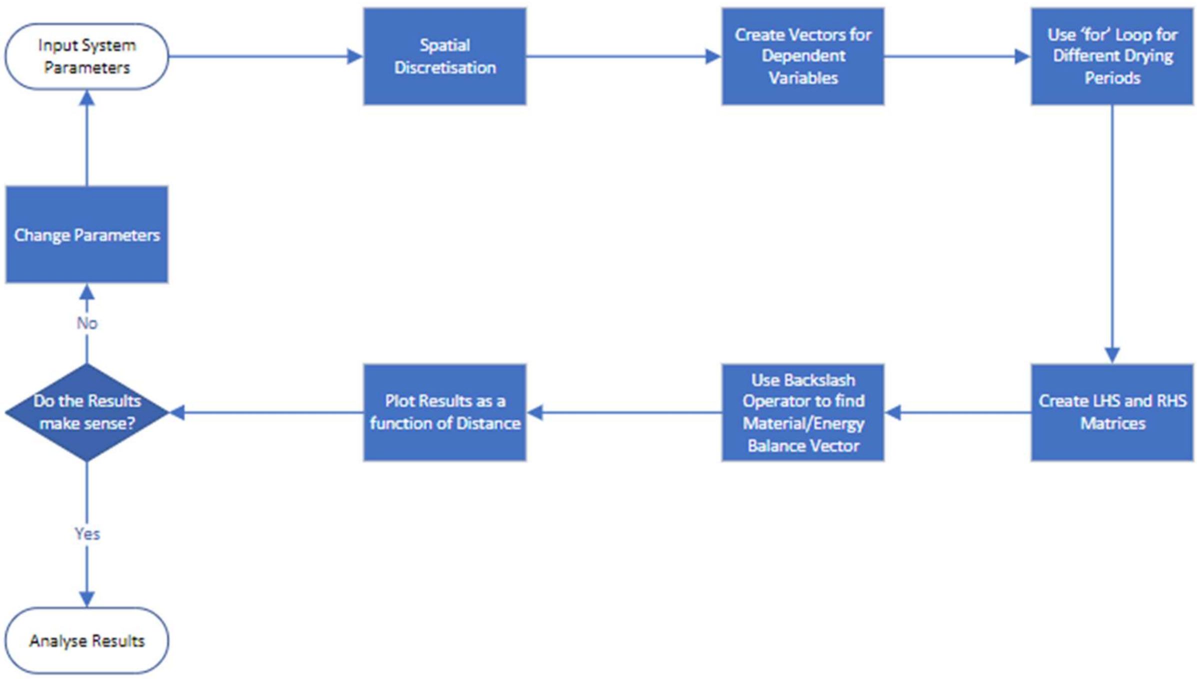


Figure 2.18: MATLAB Flowchart

Limitations posed by using MATLAB include computational errors, as well as illogical features in the model, such as increasing moisture content. Rounding errors also cause differences in results. A check was performed for point 50, where $X = 0.3890$, for the dimensionless ratio α.

$$\alpha = \frac{\frac{1}{\rho_s}}{\frac{1}{\rho_s} + \frac{X}{\rho_w}} = \frac{\frac{1}{1500}}{\frac{1}{1500} + \frac{0.389}{1000}} = 0.6313$$

$\alpha = 0.6315$ in MATLAB, thus rounding errors present differences in numbers calculated, although differences are negligible. More detailed design must consider these differences however, and account for them in design.

3. Unit Optimisation

Optimisation of the dryer considered environmental consequences of unit operation. The green principle of operating at standard conditions does not apply to the steam, although lowering its temperature is a way to reduce carbon footprint. Based on Daud (2003), 140℃ steam is used rather than the 150℃ steam designed by the group. Due to outlet steam temperature being above boiling, condensate accumulation inside the drum is reduced, thus reducing its negative effect on heat transfer to the wall. LMTD calculations are presented in **Appendix A1**. Steam temperature at the outlet for a $12m^2$ drum area is $T_{h,o} = 106.8$℃. Heating the steam through electric boilers, using renewable electricity, further minimises footprint. Assumptions are made during calculations performed for the drum dryer. Incomplete data affects the accuracy of calculations; thus, design must incorporate safety measures to account for these errors. Further design iterations are necessary, using real data to model a realistic unit. Inaccuracies in steam flowrates, for example, could be dangerous due to high pressures in the drum. Optimisation is required to reduce energy expense, cost, and environmental impact, as well as adhering to safety principles such as operating at lower temperatures and pressures. The variation of inputs during operation is mitigated through control loops, as proposed in **Section 5.1**. The variation of desired outputs can be monitored through sampling the plastic during the batch time and adjusting the process as required. Adjustments include temperature and pressure of steam, flowrate of steam and polymer, use of induction heating, and drum speed.

3.1 Operational Limits

Assumptions:

- Drum area is $12m^2$ and $U = 600\,W\,m^{-2}\,K^{-1}$, which affects LMTD calculations. Checks demonstrate that the drum area is $11.78m^2$ thus affecting accuracy of results.
- Steam outlet temperature must be cooler than the drum wall, thus maximum polymer flowrate in gives steam out of temperature ≤ 130℃.
- For polymer flowrate calculations, specific enthalpy of steam used, $2733kJ\,kg^{-1}$, was assumed constant at 3.612 bar, or 140℃. This affects mass flowrates of steam calculated in the script, as enthalpy is a function of temperature and pressure. Enthalpy is changed for steam temperature calculations.
- Drum surface is constantly 10℃ cooler than steam inlet temperature. This is a weak assumption as heat transfer from the steam to the wall is dependent on multiple factors, and as temperature changes this assumption is unlikely to be accurate.

Flowrate of polymer onto the drum and temperature of steam were modified in MATLAB to determine operational limits of the dryer. Normal operational values for these, $3810kg/batch$ and 140℃, respectively, were used as starting points. **Table 3.1** summarises the results, to 4 significant figures.

Table 3.1: Operational Limits for the Drum Dryer

Polymer Flowrate	Maximum	$4345kg/batch$
	Minimum	$1597kg/batch$
Steam Temperature	Maximum	313.7℃
	Minimum	129.7℃

3.1.1 Polymer Flowrate

Flowrate was increased by increments of $5kg/batch$ until the point where temperature → 130℃. $4345kg/batch$ was reached, giving 129.9784 ℃ steam out. A second iteration, starting from $4345kg/batch$ and increasing by $0.1kg/batch$ determined maximum flow as $4345.4kg/batch$, resulting in 129.9964℃. Flow was then decreased incrementally, by $25kg/batch$. Minimum flowrate was determined as the point before MATLAB returned NaN ("not a number"); $1610kg/batch$ returned 36.2606℃, the following point did not return an outlet temperature. The second iteration, decreasing from $1610kg/batch$ by $0.2kg/batch$ determined minimum flow as $1596.8kg/batch$, where condensate temperature out was 36.0038℃. The mass flowrates of steam required for maximum and minimum polymer flows were determined. The normal case involved $4249.1kg/batch$, the maximum required $4846.2kg/batch$ and the minimum $1780.8kg/batch$. Thus, greater mass flowrate of polymer to be dried requires greater steam flow to supply heat required. Calculations for steam mass flowrates are detailed in **Section 2.2.2**.

3.1.2 Steam Temperature

Maximum operating temperature or steam was determined as the point before NaN was returned for outlet steam temperature. 313.7℃ steam was determined as the maximum, giving an outlet of 36.0027℃. It can be concluded that 36℃ is the minimum outlet temperature for the unit, any lower returns NaN in the script. Minimum operating temperature was determined from the final point where outlet temperature is cooler than drum surface, where drum surface is 10℃ cooler than the inlet. 129.6920℃ steam gave an outlet of 119.6913℃. According to ANDRITZ (2022), steam temperature for drum dryers is between 120 and 190℃, thus the minimum temperature calculated is reasonable. Temperatures higher than 190℃ could theoretically be used, although they imply high heating costs and carbon footprint. Mass flowrate of steam required was calculated. For the maximum temperature scenario, steam required is lower than the standard value, and for the minimum temperature scenario steam requirement is higher. $3783.9kg/batch$ are required for 313.7℃, and $4270.9kg/batch$ are required for 129.7℃. Thus, although temperature increase of steam raises cost, amount of steam decreases.

3.2 Composition Limits

Composition limits investigate moisture content of the polymer, using the MATLAB script for rigorous mass and energy balances (cf. **Section 2.3**). Decreasing initial moisture content from 0.6667 to 0.65 causes the material balance graph to drop below 0.1, to 0.0999958. This demonstrates an issue with the model as moisture content should only decrease from initial to final values. Similarly, issues with the model are demonstrated when increasing moisture content, as there seems to be no maximum moisture content, the script runs without error no matter how high the initial moisture content.

3.3 Upgrade Options

To regulate moisture content in the event of excess or unevenness, an inductor and temperature sensor control system can be applied (Rodriguez et al., 1996). The infrared temperature sensor can detect moisture unevenness and remove 'wet zones' using the inductive heater. The heater is energized when required, creating an electromagnetic field which intersects the drum, generating heat from the resistance to the current. Thus, moist areas can be dried without over-drying the rest of the product. The sensor can also detect absence of product on the drum (Rodriguez et al., 1996). If the product is too dry, spray feeding can be employed to apply more product to the drum (Tang et al., 2003). This control system was thus included in the drum dryer design.

4. Mechanical Engineering Design

4.1 Material Selection

Assumptions:

- Chromium coating on the drum is very thin, thus has negligible effect on thermal conductivity.

Initial Group Design only involved superficial material selection, due to time constraints. Type 304 stainless steel was selected, due to its common usage in industry. Further material investigation was to be performed in drum dryer design, using the software GRANTA EduPack (2009); various materials were tested. For the drum metal, selection involved ferrous metals, as stated by SinoDryer (2021), with sufficient thermal conductivity and reasonable price. Several were chosen for comparison to AISI 4140 steel, which is mentioned for drum usage by Onduk et al. (2009). The drum metal is coated in Chromium 0.2 mm thick (Onduk et al., 2009). Thermal conductivities for each metal, given by EduPack (2009), were used for drum thermal conductivity in MATLAB to determine thickness of metal that would give a temperature closest to 345.2K. Thickness and density of the metal, taken from EduPack, were used in a separate MATLAB script to determine weight of the drum. Hardness, also obtained from EduPack, was also evaluated. **Table 4.1** summarises the information gathered. Total thickness includes 0.2 mm of Chromium, which is included in weight of the drum, although its effect on thermal conductivity (as well as hardness in the table) is neglected. **Figure 4.1** presents the graph used for initial material screening.

Table 4.1: Drum Material Selection

Material	Weight (kg)	Total Thickness (m)	Hardness (HV)	Thermal Conductivity (W m^{-1} K^{-1})
ENGJL100	712.8	0.012	90-216	61
ADI 900	721.8	0.0045	291-325	22
AISI 4140	779.1	0.0085	183-223	42.6
AISI 429	787.4	0.0052	140-190	26
AISI 205	792.4	0.0032	195-245	16
AISI 4130	795.3	0.0087	145-185	43.25
AISI 1025	798.3	0.011	108-173	54.05

AISI 4140 appears to be the best choice, as it has high thermal conductivity and hardness, whilst remaining relatively lightweight. High thermal conductivity is required to ensure sufficient heat transfer from the steam to the plastic, high hardness is required to avoid abrasion to the drum (e-Krishi Shiksha, 2012).

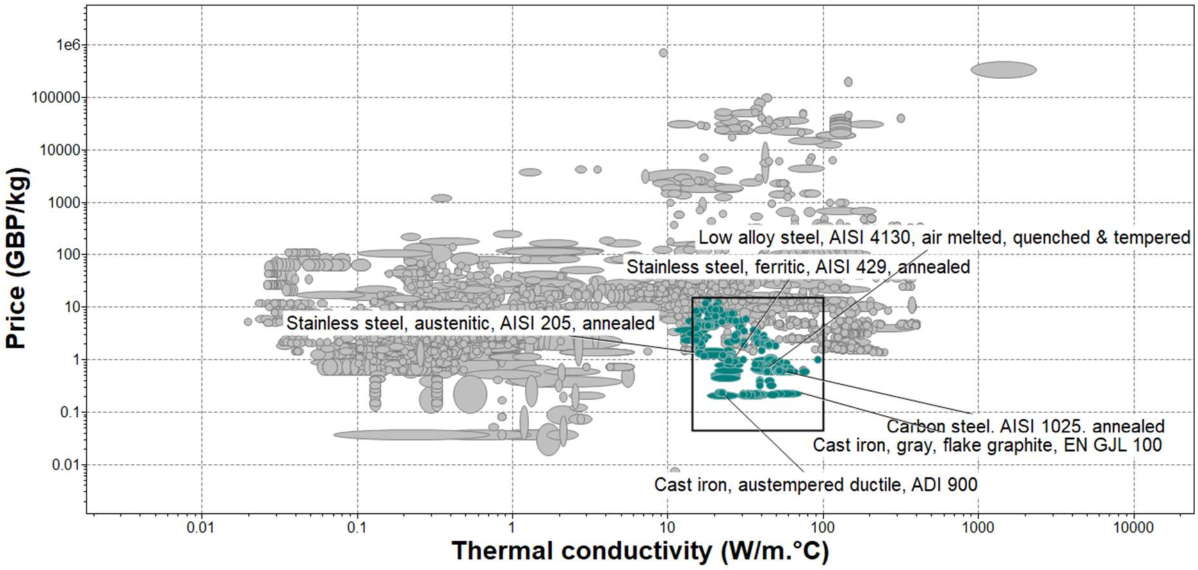


Figure 4.1: Material Selection for Drum, based on Price and Thermal Conductivity

According to Onduk et al. (2009), a high-speed steel is used for the knife. Suitable materials were narrowed down using EduPack, based on hardness, price, and “very good” wear resistance, presented in **Figure** and **Table 4.2**.

Table 4.2: Knife Material Selection

Material	Hardness (HV)	Price (£ kg^{-1})
AISI M3 Class 1	720-880	5.52-6.08
AISI M3 Class 2	720-880	5.52-6.08
AISI M33	700-840	6.77-8.16
AISI M4	720-880	5.62-6.17
AISI M42	840-1040	6.69-8.00
AISI M47	840-1040	5.7-6.72
AISI M7	720-880	4.18-4.7

Based on price and moderate hardness, as regrinding is more difficult with greater hardness (EduPack, 2009), the chosen metal for the knife is AISI M7.

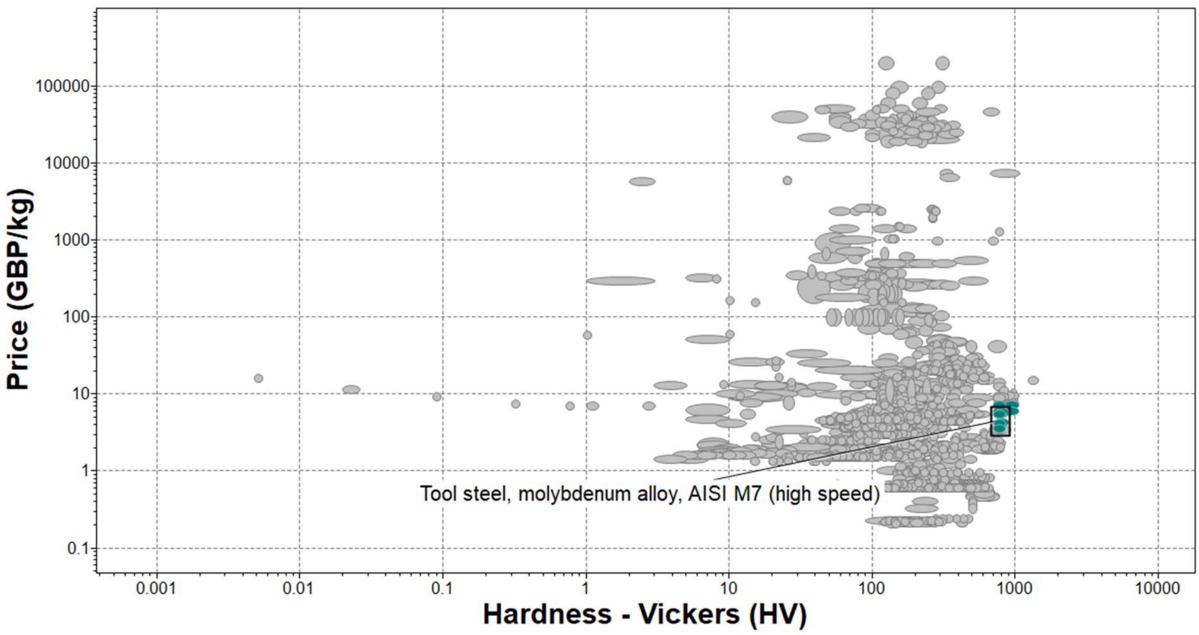


Figure 4.2: Material Selection for Knife, based on Price and Hardness

4.2 Component Dimensions

Assumptions:

- Diameter and metal thickness of the drum and applicator rolls are proportionate.
- Knife holder materials are assumed to be aluminium and composite materials, with an assumed density of $2000\ kg\ m^{-3}$.

Based on drum length of 3 metres, knife blade options given by F.A. Schmidt (2022) are $3015 \times 155 \times 3.5mm$ or $3020 \times 165 \times 2.0mm$. The latter was selected for its sharper blade and smaller volume ($9.966 \times 10^{-4}\ m^3$ compared to $1.636 \times 10^{-3}\ m^3$). Since $\rho_{AISI\ M7} = 7955\ kg\ m^{-3}$ (EduPack, 2009), weight of the knife was calculated as $7.928kg$. The knife holder with the knife is $3020 \times 325 \times 200mm$, and without the knife, at an angle of 22°, it is $3020 \times 263.2 \times 200mm$. Materials are assumed aluminium and composite materials (Valmet, 2017), with an assumed density of $2000\ kg\ m^{-3}$. Weight of the knife holder is $318kg$.

Applicator rolls are of the same materials as the drum, AISI 4140 coated with chromium. Outer diameter 0.24m is taken from Group Design, as well as number of rolls, 4. Length of each roll is 3m, like the drum. As outer diameter is roughly 5 times smaller than the drum, metal thickness of each roll is 5 times smaller; 1.7mm thick, of which coating thickness is 0.2mm. Using the MATLAB script applied to the rolls rather than the drum, individual weights of $29.66kg$ were calculated, thus a total of $118.6kg$.

The vapour hood is designed based off a model presented by Morgui (2022), with dimensions $1.05 \times 0.9 \times 0.4m$. 1mm thick AISI 304 is used, the weight of the unit is $38kg$.

The main frame is constructed with AISI 4140, weighing $20{,}320kg$.

Motor and steam/condensate pipe weights are not included in total weight calculations.

Total weight of the drum dryer unit is approximately $21{,}580kg$.

4.2.1 Knife Angle Optimisation

A doctor knife removes the plastic, in flakes, from the drum, sitting at an angle between 15 and 30° from the drum surface (e-Krishi Shiksha, 2012; Onduk et al., 2009). Optimisation of this angle prevents blunting of the knife, thus lowering power consumption (Onduk et al., 2009). According to

Onduk et al., the advised angle is between 22 and 28°; if the knife is new, the angle is adjusted to 22° (Onduk et al., 2009). Steeper angles are used after regrinding the knife (Onduk et al., 2009). If the knife angle is smaller than 22°, complete removal of product becomes difficult; if the angle is bigger than 28°, the scraper may abrade the drum (Onduk et al., 2009). Abrasion may also occur from excessive pressure on the drum, which increases energy requirement and the risk of metallic shavings in the product (e-Krishi Shiksha, 2012). Throughout operation, the knife is ground several times. Once knife length decreases to lower than 100 mm it should no longer be used (Onduk et al., 2009). Knife lifetime may be increased sevenfold by adjusting contact angle throughout usage; after this it requires replacement (Onduk et al., 2009).

4.3 Consideration of Temperature, Pressure and Expansion Effects

Assumptions:

- Force applied by knife is 500N (Onduk et al., 2009).
- Coefficient of friction applies to the smooth drum surface, thus is 0.1 (Bird and Chivers, 1993).
- Knife properties: thermal conductivity, density and specific heat capacity apply to AISI M7, taken from EduPack (2009).
- The difference between expansion, due to temperature, and reduction, due to wear, in knife length is assumed to be the difference in knife length between beginning and end of a batch.
- Decrease in knife length due to wear is assumed even across width.
- The quantitative effect of knife angle on wear rate is ignored. The qualitative effect of varying angle to increase lifetime is considered in **Section 4.2.1**.
- The effect of regrinding on knife length is ignored.
- Wear coefficient for tool steels is assumed applicable to the knife; $k_{wear} = 1.3 \times 10^{-4} mm^3 N^{-1} m^{-1}$(Yang, 2003).

Temperature rise of the knife due to friction was evaluated to determine expansion (Physics Stack Exchange, 2017).

$$\Delta T = \sigma \mu_{friction} v \sqrt{\frac{t}{\pi k_{knife} \rho_{knife} c_{knife}}} \tag{13}$$

$$\sigma = \frac{F}{A} = \frac{500N}{3.02m \times 0.002m} = 82{,}780Pa$$

$$v = \pi D V_{rc} = 0.1964m\ s^{-1}$$

$$\Delta T = (82{,}780Pa)(0.1)(0.1964m\ s^{-1}) \sqrt{\frac{(21{,}600s)}{\pi(28.3Wm^{-1}K^{-1})(7955kgm^{-3})(471JK^{-1}kg^{-1})}} = 13.09K$$

Expansion effects due to temperature change of the metal are evaluated using the following, from Lumen (2022):

$$\Delta L = \alpha_{expansion} L \Delta T \tag{14}$$

Thermal expansion coefficients and linear expansion of various metals are summarised below. Calculations are presented in **Appendix C1**.

Table 4.3: Expansion Effects on the Drum Dryer

	Material	Thermal Expansion Coefficient, $\alpha_{expansion}$ μm m^{-1} K^{-1}	Linear Expansion, ΔL μm
Drum	AISI 4140	12.2	10.63
	Chromium	6.5	0.1365
	TOTAL	-	≈0.01 mm
Knife	AISI M7	11.55	24.95

Expansion of the knife and drum must be accounted for during operation. However, the knife is worn down through usage, thus its reduction must be considered. Volume loss of the knife throughout operation gives reduction in knife length. The difference between expansion and reduction in knife length is assumed to be the difference in knife length between beginning and end of a batch. From Ripoll et al. (2022):

$$\Delta V = k_{wear} F v \Delta t \tag{15}$$

$$\Delta V = (1.3 \times 10^{-4} mm^3 N^{-1} m^{-1})(500N)(0.1964m\ s^{-1})(21{,}600s) = 275.7mm^3$$

Reduction in knife length from wear is thus:

$$\Delta L = \frac{275.7mm^3}{(3020 \times 2)mm^2} = 0.04565mm$$

Total change in knife length over one batch:

$$\Delta L = (24.95 - 45.65)\mu m = -20.7\mu m$$

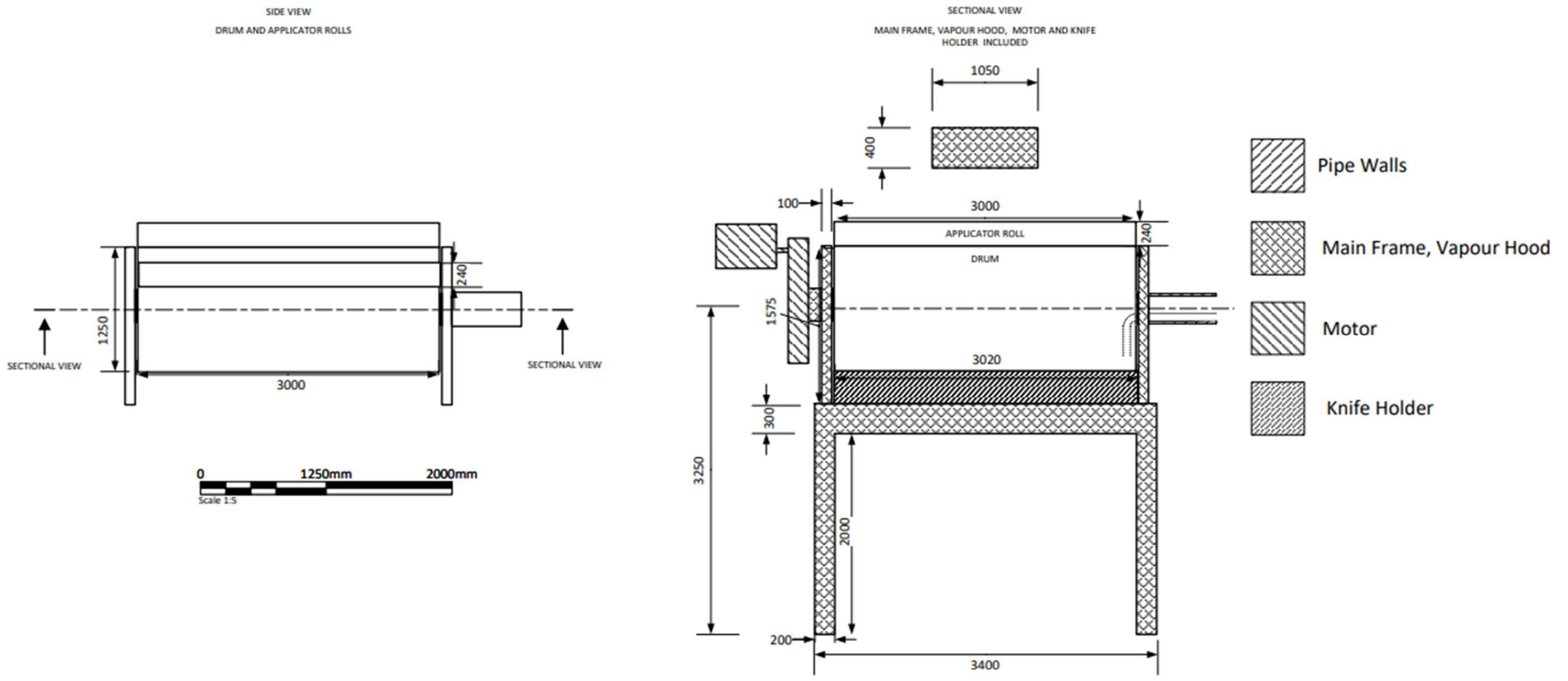
Further calculations are performed in **Appendix C2**. Knife lifetime is expected to be 3 years.

4.4 Design Procedures and Codes

The materials used must be suitable for contact with food, as the plastic has food packaging application. Attention must be placed on using the material at the recommended temperature range, selecting the appropriate material for the type of food processing, and the material's durability in maintenance and cleaning processes (Krysiak, 2022). As the final plastic product will come into contact with food products in packaging applications, care must be taken to ensure that there is no contamination of the product by the materials of the units in the process (EFSA, 2022). The materials of the equipment used for this process are defined as food contact materials (FCM), thus the FCM must be sufficiently inert so that their properties do not adversely affect consumer health or food quality. This is achieved through the European Food Safety Authority's evaluation of the product safety, testing, and legislation (EFSA, 2022). Currently, the UK has retained EU law in order to regulate FCM (EFSA, 2022). The EU standard that applies to food contact materials is EC1935/2004 (European Parliament, 2016).

The most used materials in food processing equipment are variations of stainless steel, as stainless steels provide strong resistance to corrosion associated with the food industry (Dewangan et al., 2015). Materials used must have appropriate properties for all reasonably foreseeable operating conditions. They must not be significantly affected by ageing or corrosion. Suitability of material regarding fabrication must be considered; components may require welding. Metallic liners are used to resist corrosion. Materials selected for the internals must be compatible with the materials chosen for the main components (Health and Safety Executive, 2022).

4.5 Engineering Drawings



TITLE
DRUM DRYER
SIDE AND SECTIONAL VIEW

DRAWN BY ALEX RANERI DATE 5/1/2022
CHECKED BY ALEX RANERI REVISED 5/1/2022

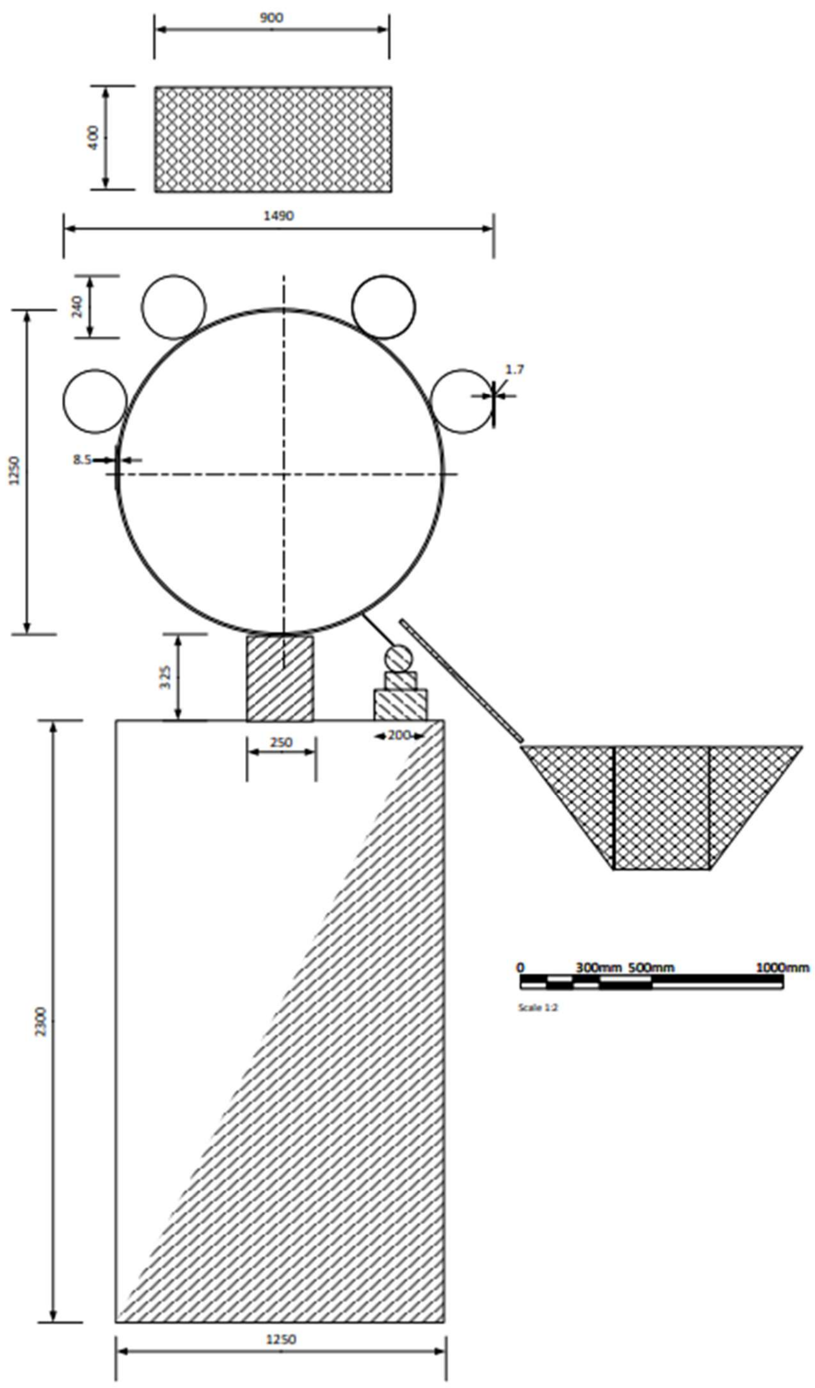
UNIVERSITY OF BATH

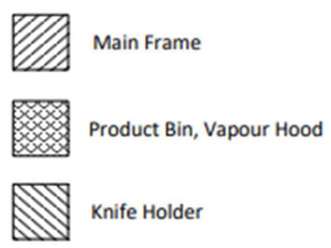
MATERIALS: AISI M7 (KNIFE), ALUMINIUM and COMPOSITE MATERIALS (KNIFE HOLDER), AISI 4140 (DRUM, APPLICATOR ROLLS, MAIN FRAME), AISI 304 (VAPOUR HOOD), CHROMIUM (SURFACES OF DRUM AND ROLLS)

SIZE	VERSION	DWG NO	REV
mm	1.2	1	3

FIGURE: 4.3 a

SCALE 1:5 UNITS: METRIC SHEET 1 OF 3





TITLE
DRUM DRYER
CROSS SETIONAL FRONT VIEW

DRAWN BY ALEX RANERI DATE 5/1/2022
CHECKED BY ALEX RANERI REVISED 5/1/2022

UNIVERSITY OF BATH

MATERIALS: AISI M7 (KNIFE), ALUMINIUM and COMPOSITE MATERIALS (KNIFE HOLDER), AISI 4140 (DRUM, APPLICATOR ROLLS, MAIN FRAME), AISI 304 (VAPOUR HOOD), CHROMIUM (SURFACES OF DRUM AND ROLLS)

SIZE	VERSION	DWG NO	REV
mm	1.2	2	3

FIGURE: 4.3 b

SCALE 1:2 UNITS: METRIC SHEET 2 OF 3

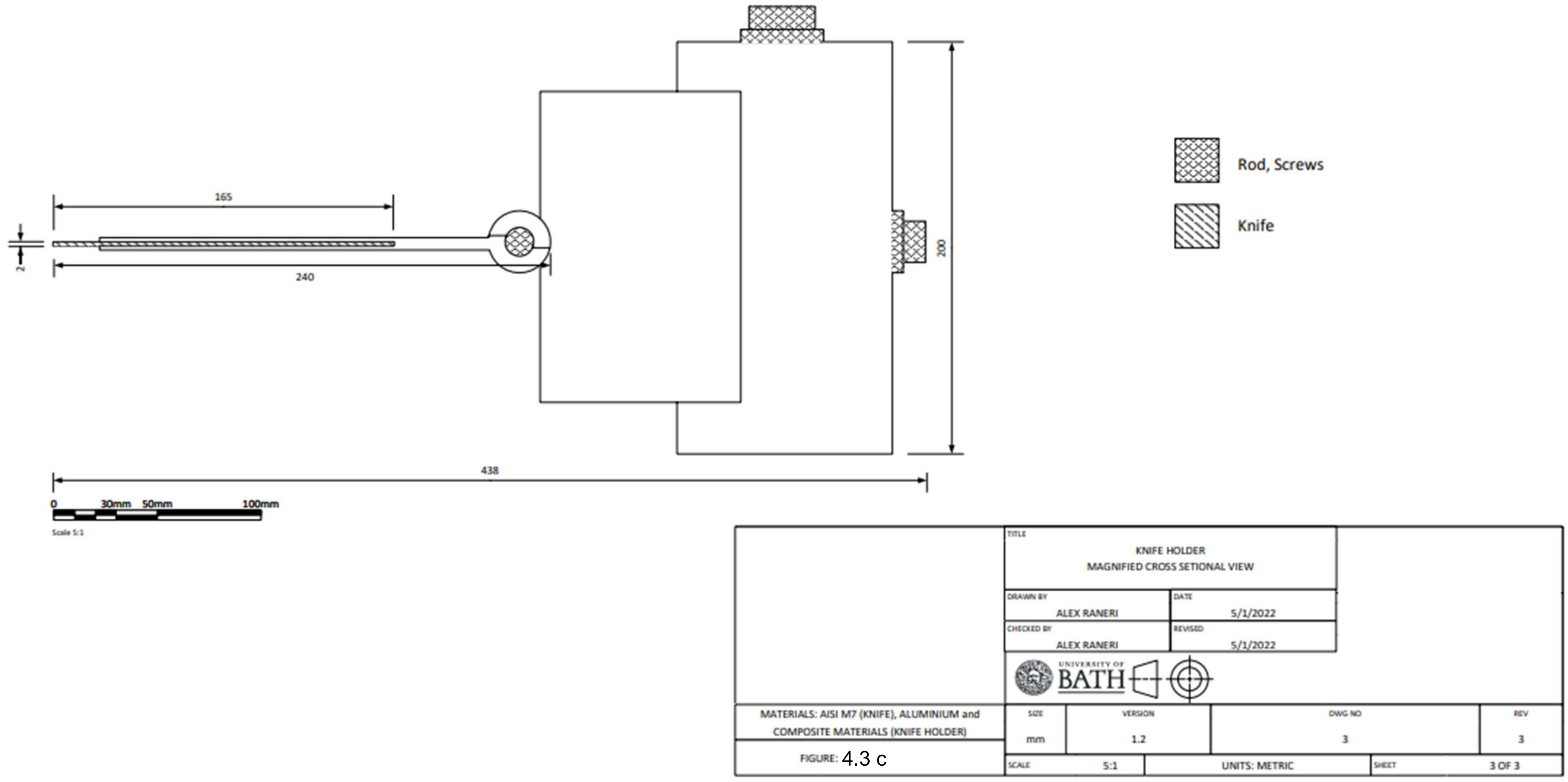


Figure 4.3: Drum Dryer Mechanical Drawings; a. Side Views b. Front View c. Knife Holder

5. Drum Dryer Control System

5.1 P&ID and Control

Final moisture content of the plastic can be regulated; moisture unevenness is dependent on both time and drum width (Rodriguez et al., 1996); thus, a control system must be able to mitigate both, through an actuator. The presence of 'wet zones' along drum width requires local drying of zones, to avoid over-drying the rest of the product; an inductive heater may be used to this effect (Rodriguez et al., 1996). The drum motor controls drum rotation speed for varying drying duration. The steam admission valve controls steam pressure, thus drum surface temperature. Using the temperature sensor and actuator mentioned in **Section 3.3**, steam pressure, rotation speed, and induction heating can all be varied in a control loop (Rodriguez et al., 1996). High moisture in the product is due to low temperature, thick film, high total solids, and fast rotation speed (e-Krishi Shiksha, 2012); the variation of steam pressure/temperature, film thickness, rotation speed, and the use of induction heating can thus solve moisture issues. The inductive electric heater used by (Rodriguez et al., 1996) is 50 Hz, with maximum power 3.4kW, placed at the bottom of the drum. To control moisture unevenness with time, a PI loop controller was used, due to its simplicity. It was a single-input/single-output control, where drum rotation speed was the manipulated variable, it was determined that manipulating drum rotation speed rather than steam pressure was more effective (Rodriguez et al., 1996). Rodriguez et al. (1996) found that using the former as the manipulated variable allowed for control of moisture content within $\pm 0.001 kg\ kg^{-1}$. Moisture can vary with width along the drum, due to uneven product distribution, or accumulation of non-condensable gases which impedes heat transfer. The heater can be used to mitigate this, controlled by a PI loop, without over-drying any zones. Two heaters are required in industrial use, to correct each side of the drum (Rodriguez et al., 1996). Feedback loops are used for control, where transmitters take measurements at a point after a valve, informing indicator controllers which vary the degree to which valves are opened. This allows for faster response time as feed forward PID control, which requires greater computational power, is not used.

The P&ID for the drum dryer is presented in **Figure 5.1**.

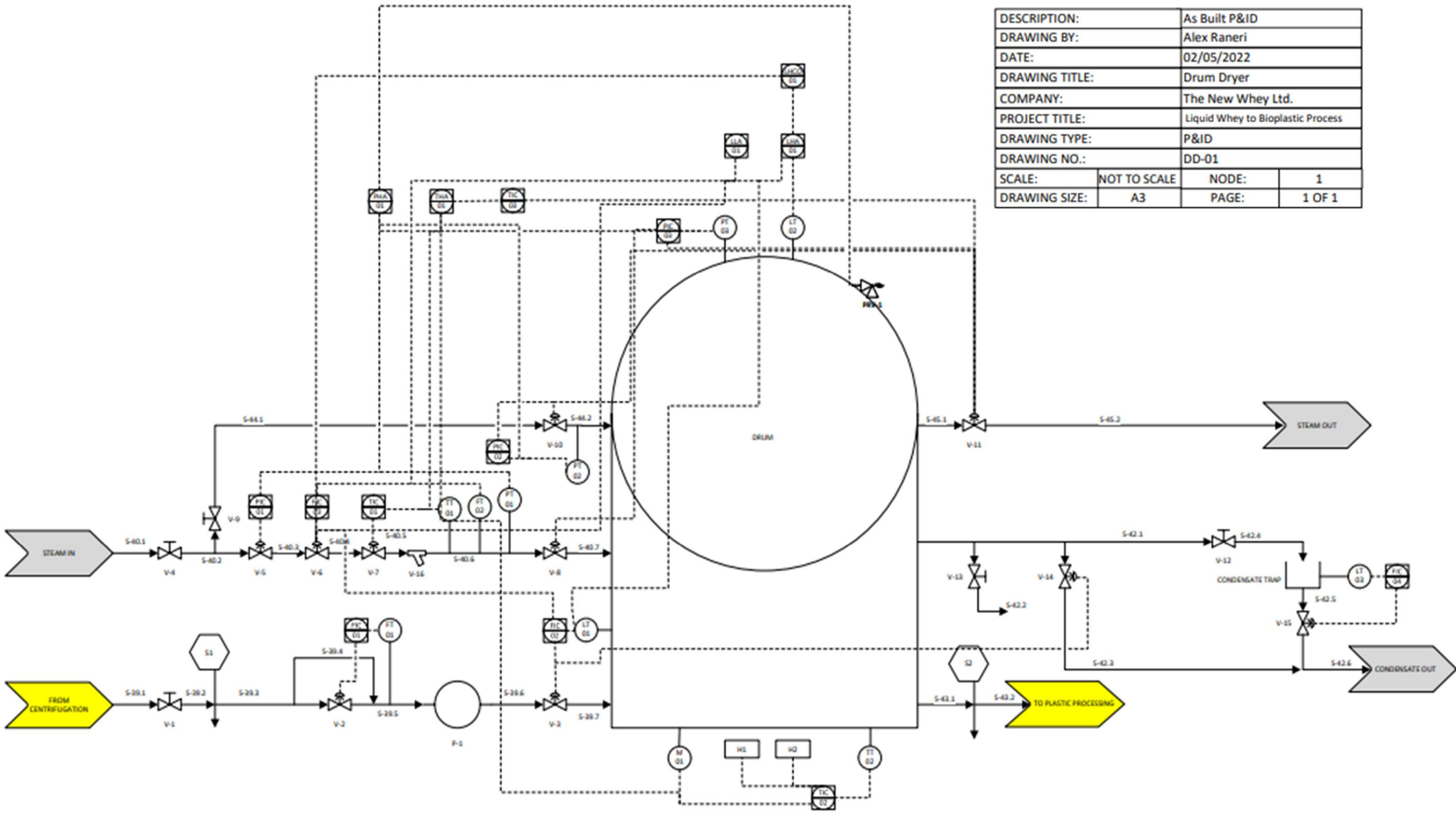


Figure 5.1: Drum Dryer P&ID

5.2 Safety

Safety must be considered throughout the entirety of the design process to minimize hazardous consequences affecting the personnel of the process plant and the surrounding areas. Minimising hazardous process conditions such as high temperature and pressure makes the unit inherently safer, such as by using 140℃ steam rather than 150℃. Hazards related to heavy lifting are addressed with emphasis on staff training and ethical working conditions. Other hazards such as the knives in the drum dryer are mitigated with a suitable start-up and shut down strategy. Any waste must be properly treated and not released into the surroundings. Following these considerations, the process can be made safer, with further hazards mitigated through control and alarm systems.

The evaluation of safety is structured through a HAZID, HAZOP, and a LOPA, presented in **Tables 5.1**, **5.2** and **5.3**, respectively. The HAZID informed a HAZOP workshop, devising safeguards to mitigate any hazards and operability considerations. A P&ID could thus be created, **Figure 5.1**. For the safety of workers and residents, actions proposed in the HAZID, HAZOP, and LOPA must be implemented.

Table 5.1: Hazard Identification (HAZID) for the Process

Guideword	Hazard	Consequence	Safeguards	Comments
Natural Disasters	Earthquakes Severe weather Floods	Equipment/infrastructure damage/failure Economic loss due to production loss and repair costs Utility failure	Reinforcements on units and a geographical survey on location before construction Emergency shutdown plan for each scenario.	Staff training on the Emergency Action Plan and regular emergency drills. Evacuation protocols in place. Regular inspections of structural integrity
Location	Loud mechanical noises Emissions Wildlife	Noise pollution Air pollution Injury of cattle	Ensure location is chosen far from housing or cattle fields. Minimise emissions Fence off plant to local surroundings	Discuss the plant layout with residents and businesses, ensure their opinion is taken into consideration in the design phase
Plant layout	Confined spaces Proximity hazards (e.g., electrical source near water)	Emergency escape routes may be restricted Ignition, explosion	Designated routes that everyone on-site is aware of Strategic design: ensure consideration is taken to allow reasonable space between equipment	Hazards discussed taken into consideration in plant layout design
Mechanical equipment	Sharp blades	Personnel injury from serious cuts	Hazard zones with clear signage Cut-resistant gloves for personnel Ensure isolation of equipment during maintenance, pressure alarms	Regular maintenance and checks to equipment

Utility Streams	High temperature steam inlet	Burns to personnel	Hazard zones with clear signage Protective gloves when handling steam pipelines and provide insulation, temperature alarms	First aid training and supplies on site
Sources of ignition	Electrical equipment Pumps and heat exchangers Onsite smoking Mechanical sparks	Fire damage Injury to personnel Explosion Equipment damage	Regular electrical safety testing No smoking signs Fire safety equipment Fire doors Ventilation	Regular maintenance Site audits Fire safety training and drills
Release of inventory	Valve leaks Tank leaks	Personnel injury from slips Hazardous reagent release Loss of product yield	Storage in closed containers Cleaning up spills immediately System shutdown/unit isolation for repairs	Regular maintenance of equipment Incident reporting procedure to prevent further leaks
Effluent disposal	Environmental impact Transportation	Spillage Damage to aquatic life and land contamination Floods on site	Safe disposal strategy Waste treatment partner Safe transportation	Follow legal disposal protocols and regulations

Electrical Hazards	Pumps Heat Exchangers Control systems	Failure of pumps causing system delay Incorrect heating affecting products Alarm and control failure Fires as above in ignition sources	PAT testing Away from water Insulated cables Covered switches	Regular maintenance and inspection of electrical equipment Safety protocols and training
Heavy Objects	Product removal and solids handling Maintenance, equipment removal, and replacement	Human injury Equipment damage Loss of yield	Safe handling procedures Only trained professionals Clear surrounding area First aid Use of appropriate equipment	Use of forklifts in place of humans lifting heavy objects

Table 5.2: Hazard and Operability Analysis (HAZOP) for the Drum Dryer

Case No.	Parameter	Guideword	Deviation	Cause	Consequence	Action /Safeguard	Severity	Likelihood	Risk
1	Temperature	More	Temperature of stream 40 too high	Utility boiler malfunction	High temperature and pressure steam may damage equipment	Temperature transmitter, temperature indicator control, temperature high alarm, all connected to stream 40, to vary opening of valve 7. Temperature indicator control for purge valve 11 in stream 45, to fail open if temperature too high.	3	2	6
2			Temperature of plastic too high	Over drying	Product quality not achieved	Temperature transmitter (infrared thermometer), temperature high alarm, temperature	1	2	2

						indicator control. Temperature indicator control varies drum rotation speed, it is sped up to decrease drying duration.			
3		Less	Temperature of stream 40 too low	Same as Case No. 1	Same as Case No. 2	Temperature transmitter, temperature indicator control, all connected to stream 40, to vary opening of valve 7.	1	2	2
4			Temperature of plastic too low	Steam temperature too low	Same as Case No. 2	Temperature transmitter (infrared thermometer), temperature indicator control. Temperature indicator control switches on induction heaters and varies drum rotation speed; it is slowed down to increase drying duration.	1	2	2
5	Pressure	More	Pressure of stream 40 too high	Same as Case No. 1	Same as Case No. 1	Pressure transmitter, pressure indicator control, pressure high alarm, all connected to stream 40, to vary opening of valve 5. Pressure transmitter for stream 44. Pressure indicator control for purge valves 10, 11 in streams 44 and 45; 11 to fail open if pressure too high.	3	2	6
6			Pressure inside drum too high	Same as Case No. 1	Same as Case No. 1	Pressure transmitter, pressure indicator control, pressure high alarm, all connected to streams 40	3	2	6

						and 45, to vary opening of valves 8 and 11; 11 to fail open if pressure too high. Pressure release valve for drum.			
7			More than maximum allowable pressure in drum	Same as for Case No. 15, 1	Same as for Case No. 15	Same as for Case No. 15, 6	4	1	4
8		Less	Pressure of stream 40 too low	Same as Case No. 1	Same as Case No. 2	Pressure transmitter, pressure indicator control, all connected to stream 40, to vary opening of valves 5 and 8.	1	2	2
9			Pressure inside drum too low	Same as Case No.1	Same as Case No. 2	Same as Case No. 8	1	2	2
10	Flow	No	No flow in stream 39	Piping blockage upstream Failure of valves 2 or 3 Operator failure closing valve 1 during operation Pump 1 failure	No plastic drying, potential for drum damage due to knife, potential for overpressure	Bypass stream around valve 2 Level transmitter, level indicator control, all connected to stream 39, to vary opening of valve 3, to fail open.	2	2	4
11			No flow in stream 40	Piping blockage upstream Failure of valves 5, 6, 7 or 8, or of y-strainer valve 16 Operator failure closing valve 4 during operation	No plastic drying	Same as Case No. 4	1	2	2

				Utility failure					
12		More of	More flow in stream 39	Valve 3 fails open Control or operating failure of valves 2 or 3	Greater steam requirement due to larger plastic throughput. Under drying of product.	Flow transmitter, flow indicating controller for valve 2. Level transmitter and flow controller for drum and valves 3 and 6. Same as Case No. 4	1	2	2
13			More flow in stream 40	Valve 8 fails open Control or operating failure of valves 5, 6, 7 or 8	Same as Case No. 1	Pressure transmitter, pressure indicator control, pressure high alarm, all connected to drum and stream 45, to vary opening of valve 11, to fail open if pressure too high. Pressure release valve for drum.	3	2	2
14		Less of	Less flow in stream 39	Pump failure Control or operating failure of valves 2 or 3 Pipe blockage	Less steam requirement thus potential for over drying product. Lower plastic production.	Same as Case No. 12	1	2	2
15			Less flow in stream 40	Control or operating failure of valves 5, 6, 7 or 8 Pipe blockage Valve 16 blockage due to particulate build-up	Same as Case No. 2	Same as Case No. 8, as well as potential to open valve 9 to let more steam into the drum.	1	3	3
16	Fire	Present	Fire in the plant	Smoking or other ignition sources	Possible explosion Damage to reactor Loss of product	Fire safety protocols onsite	4	1	4

						High pressure alarms linked to pressure relief valve High pressure indicators to shut off inlet flows if pressure too high			
17	Level	More	More level in the drum	Flow deviations of inlet stream(s)	Spillage or leaks causing injury to personnel High pressure in drum, see Cases No. 6 and 7	Level transmitter on drum for both plastic and steam (external and internal) Flow indicator control Level high alarm Level high cut off Add tolerance in drum sizing to allow for excess level Clean up spillages immediately	3	2	6
18		Less	Less level in the drum	Flow deviations of inlet stream(s)	See Cases No. 8, 9, 14, 15	Level transmitter on drum Level indicator control Level low alarm Level transmitter All connected to valves with respective flow controllers	3	2	6
19	Composition	Different from	Composition of polymer	Upstream deviations	Decreased product quality	Sampling points on streams 39 and 43 during batch time where correctional action can be taken to adjust inlet flows.	1	3	3
20	Operation and maintenance	No	No process operations	Power or utility failure	No product produced resulting in loss of profit	Back-up power supply	2	2	4

				Worker shortage or strikes		Ethical working conditions and liaise with workers union Hire and train sufficient staff			
21			No maintenance	Maintenance not scheduled	Greater hazards Equipment failure Inadequate product quality	Develop operations and maintenance philosophy: plan for regular maintenance	4	2	8
22		Other Than	Insufficient process operations and maintenance	Worker shortage Delays caused by maintenance Supply chain delays	Greater hazards or process errors due to lack of staff. Lower production rate leading to loss of profit	Schedule maintenance between batches to minimise downtime	4	2	8
23	Utilities	No	No power or electricity	External power cuts and outages	Failure of control systems due to lack of electricity. Consequences as Case No. 1-21	Back-up power supply	4	2	8
24	Instrument air	No	No air supply to control systems	Malfunction in air supply due to piping, fouling, and/or lack of lubrication	Failure of control and alarm systems Greater process risks caused by lack of control in reactor	Regular maintenance and replacement of actuators	4	2	8

Impact (A)

Likelihood (B)

	1-Negligible	2-Minor	3-Moderate	4-Significant	5-Severe
1-Very Unlikely	Low	Low	Low Med	Medium	Medium
2-Unlikely	Low	Low Med	Low Med	Medium	Med Hi
3-Possible	Low	Low Med	Medium	Med Hi	Med Hi
4-Likely	Low	Low Med	Medium	Med Hi	High
5-Very Likely	Low Med	Medium	Med Hi	High	High

Figure 5.2: Risk Ranking Matrix

In industry, it is important that the HAZOP is carried out by a multi-disciplinary team. The HAZOP leader who will prepare the study and lead discussions relating to the study is to be affiliated with the process being analysed. A secretary will prepare any worksheets, record discussions, and prepare the HAZOP reports. A project engineer, process engineer, electrical engineer, safety engineer, operating team leader and maintenance engineer for the company are also valuable in a HAZOP, as for efficient running of the process at least one person for each relevant discipline associated with the project should be aware of the associated hazards and contribute to risk minimisation methods, with each person bringing a different area of expertise that will ensure all hazards are considered.

Due to the nature of the project, the HAZOP was conducted individually however, thus it requires checking from other individuals to ensure safety is upheld. Despite this, it was based off the Group Design HAZOP, to ensure pertinency of the safety measures introduced. Chosen guidewords were followed throughout the process considering deviations in temperate, flow, level, composition, operations and maintenance, utilities, pressure, instrument air and fire. Safeguards were devised to mitigated consequences and later applied to the P&ID, **Figure 5.1**.

The HAZOP conducted above is aimed to assess the hazards and operability of the drum dryer. A risk ranking matrix (**Figure 5.2**) was then used to evaluate the severity or impact and likelihood of each hazard in a semi-quantitative manner based on experience of the design team and process knowledge. The final score or colour of the hazard was then used to prioritise mitigations including temperature and pressure control and alarm systems along with flow and level controls and alarms. The main aim of the HAZOP was to protect against elements of process safety and operational safety. In cases 1-4 for deviations of temperature in the reactor, the main objective was to mitigate any increase in temperature cause by utility failure, and the decrease in temperature caused by lower temperature steam. This was done by adding temperature controls on the initial P&ID. In cases 10-15, for flow deviation, and 17-19, for flow and composition deviation, the safeguards added to the P&ID included an extensive system of flow indicator controls and transmitters connected to level transmitters and level high alarms to mitigate overfilling or underfilling.

Finally, to mitigate risks from fire and pressure cases 5-7 and 15, a pressure indicator, pressure high alarm, and pressure relief valve (PRV) were added with the PRV-1 to be rated at 10% above system operating pressure, 3.973 bar as recommended from engineering practice (Sinnott and Towler, 2005). Valves were set to fail open to avoid build-up of steam inside the drum. For operational safety, various mitigations were addressed to facilitate smooth running of the dryer. This includes ethical working environment, fire safety training, and staff training on procedures to ensure operations are sufficiently staffed. Additionally, operations and maintenance were also considered with a need for a comprehensive operations and maintenance strategy to ensure maintenance is carried out to prevent valve and pipe blockages in the system leading to hazardous consequences due to equipment failure. Finally, instrument air failure and utilities failure were considered with most mitigation strategies addressed in other guidewords along with the need of backup power supply and scheduled maintenance to prevent deterioration of systems.

An example LOPA is presented for drum overpressure, which could cause a rupture and fatality to nearby persons. Tolerable frequency for a single fatality is 0.0001 per year; for multiple fatalities the frequency is 0.00001 per year. Due to the nature of the drum dryer, which is unlikely to be isolated from workers, the expected frequency of drum overpressure must be below 0.00001 per year. The following are assumed:

- The frequency of control failure was 1
- The probability that multiple workers would be present in the event of overpressure was 1
- Thus, boiler malfunction was assumed due to PRV failure

The probability of the initiating event was determined; overpressure is due to utility boiler malfunction, as mentioned in the HAZOP, thus delivering high pressure steam to the drum. Boiler malfunction was assumed due to pressure control failure as well as the failure of the PRV on the boiler; frequency of control failure was taken as 1. The probability of the PRV not opening was calculated as 0.05 per year, an average of values presented by the Health and Safety Executive (2004). This was assumed the probability of drum overpressure, without any mitigations in place.

$$0.05\ year^{-1} > 0.00001\ year^{-1}$$

Thus, independent protection layers must be implemented to reduce the frequency of overpressure to an acceptable level. A PRV on the drum and gas shut-off valves, or electricity shut-off if utility streams are heated with renewable electricity, were implemented. The probability of failure on demand of the gas shut-off valves is 0.03 per year (Health and Safety Executive, 2004). Respective risk reduction factors of the PRV and shut-off valves are thus:

$$\frac{1}{0.05} = 20, \frac{1}{0.03} = 33.33$$

Applying these mitigations, the expected frequency of drum overpressure is:

$$Frequency = 0.05 \times 0.05 \times 0.03 = 0.000075\ year^{-1}$$

The safety measures lower overpressure risk to an acceptable pressure for a single fatality: $0.000075\ year^{-1} < 0.0001\ year^{-1}$, however the frequency is unacceptable for multiple fatalities: $0.000075\ year^{-1} > 0.00001\ year^{-1}$. Thus, further safeguards are required to lower the frequency. A purge valve, to be opened in case of high pressure, was implemented. The probability of failure on demand of an excess flow valve to fail to operate is 0.013 per year (Health and Safety Executive, 2017), which was assumed applicable to the purge valve not opening.

$$Frequency = 0.05 \times 0.05 \times 0.03 \times 0.013 = 0.00000098\ year^{-1}$$

$$0.00000098\ year^{-1} < 0.00001\ year^{-1}$$

Therefore, the frequency of drum overpressure is acceptable, implementing two PRVs, gas shut-off valves, and a purge valve. The LOPA calculations are presented in **Table 5.3**.

Table 5.3: LOPA for Drum Overpressure

Scenario	**Drum Overpressure and Multiple Fatalities due to Rupture**		
	Description	**PFD**	**Freq (yr^{-1})**
Initiating Event	**Failure of Pressure Control**		**1**
Condition Modifiers	**Probability of PRV Failure**	$\mathbf{5 \times 10^{-2}}$	
	Probability Workers Present	**1**	
Unmitigated Frequency of Consequence			$\mathbf{5 \times 10^{-2}}$
IPLs	**Probability of Drum PRV Failure**	$\mathbf{5 \times 10^{-2}}$	
	Probability of Gas Shut-off Valve Failure	$\mathbf{3 \times 10^{-2}}$	
	Probability Purge Valve does not Open	$\mathbf{1.3 \times 10^{-2}}$	
Total PFD for IPLs		$\mathbf{1.95 \times 10^{-2}}$	
Freq of Mitigated Consequence			$\mathbf{9.8 \times 10^{-7}}$

5.3 Start-Up and Shut Down Procedure

Thorough start-up and shut down procedures ensure plant safety and optimise process yield and efficiency; this section outlines the required steps for optimal operation.

Start-Up:

Start-up can pertain to a restart after a planned/emergency shutdown, or the initial unit start-up. Identical guideline and instructions must be followed for both scenarios. It must be ensured that all vessels are thoroughly cleaned and emptied of any contaminants. Vessels must also be inspected by trained staff members to identify and rectify any issues with vessel condition and specification (Criterion Technologies, 2008). Before beginning the procedure, check all equipment, utilities, valves, switches are functioning and prepared for operation (Australian Agricultural Company, 2014). As the drum uses elevated temperatures via hot fluids, it must carefully be inspected by a trained professional to maintain safety standards when starting up. Any fluid flow entryways must be checked and cleared (Criterion Technologies, 2008). Warping of the product is prevented by turning on the steam gradually as the drum is set in motion. The first plastic flakes may be over-, or under-, dried (e-Krishi Shiksha, 2012), thus initial quality may not meet the required standard.

1. For a newly chromed drum: wash the chrome surface with a 3% hydrogen peroxide solution, allow the drum to dry at room temperature for several hours. Repeat (DrumDryingResources, 2022).

2. Add water to the surface to check the chrome surface passivity. Water should wet the surface in a film and not form droplets. If the latter occurs, repeat step 1 (DrumDryingResources, 2022).

3. Blow down the main steam line of all water (DrumDryingResources, 2022).

4. Check the drum and knife for any foreign objects (DrumDryingResources, 2022).

5. Turn on the vapour hood (DrumDryingResources, 2022).

6. Check knife blade, end dams and screw conveyor product diverter shields, to ensure they are not touching the drum (DrumDryingResources, 2022).

7. Open the main condensate return valve V-12 and drain water. When empty, close the main condensate return valve (DrumDryingResources, 2022).

8. Open the condensate bypass valve V-14 (DrumDryingResources, 2022).

9. Make sure the trap valve V-15 is open (DrumDryingResources, 2022).

10. Open the air purge valve V-10 (DrumDryingResources, 2022).

11. Remove any lock-out device, to power the main panel (DrumDryingResources, 2022).

12. Lift the knives and start the drum at 15 Hz (e-Krishi Shiksha, 2012; DrumDryingResources, 2022). The drum must be monitored for noise and vibration as its speed increases to operating speed. It must not be allowed to run without product, as this wears the knives and drum surface (Australian Agricultural Company, 2014).

13. Start the exhaust blower (DrumDryingResources, 2022).

14. Ensure the steam blow down valve V-11, the y-strainer valve V-16, and the steam pressure regulator are closed or off (DrumDryingResources, 2022).

15. Open the main steam valve V-4, slowly (DrumDryingResources, 2022).

16. Blow down the y-strainer valve V-16, to clean-out the screen. Open with caution of high-pressure steam. After the blow down, close (DrumDryingResources, 2022).

17. Open the steam air regulator to bleed in steam, so that it maintains 10 psi of steam on the drum dryer pressure gage for 1 hour, then increase the steam pressure 10 psi every 15 minutes (DrumDryingResources, 2022). For a newly chromed drum, the steam pressure should be increased in increments of 5 to 10 psi every 15 minutes (DrumDryingResources, 2022). Record the initial warm-up time and pressure increments (DrumDryingResources, 2022).

18. When the steam pressure is at 15 to 20 psi on the drum gage, close the drum air purge valve V-10, condensate by-pass valve V-14 and trap valve V-15; then open the main condensate return valve V-12. Open the trap valve no more than one turn; this bleeds steam in with the condensate (DrumDryingResources, 2022).

19. The drum dryer warm-up procedure should take no less than 2.5 hours (DrumDryingResources, 2022). The initial heating of a newly chrome-plated drum should be made over a 3 to 4 hour period, with the drums in rotation (DrumDryingResources, 2022).

20. When the drum reaches the specified steam pressure, production can start (DrumDryingResources, 2022).

Shut Down:

Following the last of the plastic, flushing and cleaning of the equipment must be performed (Australian Agricultural Company, 2014). Air within the drum must be purged, and the drum emptied. Any necessary maintenance must be performed. Room temperature and humidity must be kept stable to avoid rusting. For extended periods of unuse, software backups must be performed before cutting off electricity. Heating elements must be switched off and at ambient temperature before any maintenance can be performed. If a trained worker is to inspect the drum, it must be fully emptied for safety. Plant shutdown must be avoided unless completely necessary for plant safety or required maintenance had been scheduled (Criterion Technologies, 2008). Operators must ensure the process has completely shut down, with all machinery having stopped moving entirely, before performing checks and maintenance. Care must be exercised when handling the knives due to the risk of injury. Hot steam also poses risks, thus complete venting and condensate removal of the drum is required before operators perform maintenance.

1. Turn off the feed supply hand valve V-1 and shut off the feed pump P-1 (DrumDryingResources, 2022).

2. Run out the puddle until the sheet becomes unacceptable, or the drums are clean (DrumDryingResources, 2022).

3. Raise the knife blade and retract the end dams (DrumDryingResources, 2022).

4. Stop the side screw conveyors (DrumDryingResources, 2022).

5. Turn off the main steam pressure valve V-4 and open the trap valve V-15 and condensate valve that dumps to the floor V-13 (DrumDryingResources, 2022).

6. Flush the dryer hood and drums with no less than 80℃ water (DrumDryingResources, 2022).

7. Cover machinery in plastic wrapping to protect against contamination from metal shavings and dust (Orientech, 2020).

5.4 Operation and Maintenance

Periodical checks assure quality standards are maintained. Knives must be reground regularly, after around 100 hours of use, and be of uniform sharpness and thickness. They must be flexible and easily adjusted (e-Krishi Shiksha, 2012). Uniform knife pressure against the drum must be maintained, at the lowest pressure that still performs as required (e-Krishi Shiksha, 2012; DrumDryingResources, 2022). Blade backs must not be modified or welded. Blades must be inspected for wear often, the knife holder must be inspected and cleaned when blades are replaced (DrumDryingResources, 2022). Alignment of knife and drum must be checked regularly, with a new blade. Knives must be removed from service before exceeding their lifetime. Damaged blades or holders must be replaced. Knife position must not be modified whilst the drum is turning (DrumDryingResources, 2022). The drum surface must be kept smooth, it may require resurfacing after 1000 to 3000 hours of operation (e-Krishi Shiksha, 2012). During periods when unused, an oil or paraffin wax film should be applied, to prevent rust. Condensate must be removed quickly from inside the drum, to ensure the entire interior heat transfer surface of the drum is available (e-Krishi Shiksha, 2012). Thus, the main factors influencing maintenance and cleaning during operational lifetime include wear of knives and drum surface, and rusting.

Daily maintenance activities include greasing bearings, checking filters and drains, checking drum and knives, setpoints and process variables (Australian Agricultural Company, 2014). Weekly activities include checking lubrication, seals for any leaks, and the temperature sensor. Monthly checks include wear of screws, pumps, fans, as well as re-calibration of sensors (Australian Agricultural Company, 2014).

6. Summary

The objective of the project was to produce a bioplastic film for food packaging, from waste cheese whey. 100 tonnes of whey were processed per batch, producing 2.515 tonnes of plastic. The plastic had a water content of 9%, with the rest being polymer and impurities. The drum dryer, which is the focus of this design project, was the final unit in the process, responsible for drying the plastic and forming flakes. The final design of this unit includes a drum speed of 3 rpm, respective steam temperature and pressure of 140℃ and 3.612 bar, polymer flowrate to be dried on the drum $3810 kg/batch$, and steam flowrate required for heating $4249.1 kg/batch$. Dimensions are detailed in the specification sheet presented below. Final design temperature and pressure are lower than the proposed values in the Group Design; operation was deemed acceptable at lower temperature and pressure, also reducing hazards and environmental impact. Drum speed was determined through calculation, although control loops were devised to vary this depending on rate of drying of the plastic. Steam pressure and flow, as well as plastic flow could also be varied through control loops. A PI loop was used to control local plastic moisture content using an infrared thermometer and induction heaters. Pressure loss inside the drum was determined negligible compared to pressure drop of the steam. Thus, design did not consider pressure losses or the effects of this. Expansion effects of metals due to temperature and friction, as well as volume loss of knife were considered through calculation. Further optimisation is required to determine the extent of the influence of these factors on unit operation. Materials for the drum and applicator rolls were AISI 4140 with Chromium coating. AISI M7 was used for the knife, with the holder being aluminium and composite materials. AISI 304 was used in the vapour hood. Total weight of the drum dryer unit was approximately $21{,}580 kg$, not including the motor and pipes. Initial knife angle was 22°, throughout lifetime this is changed between 22 and 28°, after regrinding. Lifetime is expected to be 3 years considering volume loss from usage. Safeguards implemented following safety exercises included alarms, valves, and sensors, as well as staff training procedures.

The final unit specification sheet is presented in **Table 6.1**.

Table 6.1: Drum Dryer Specification Sheet

UNIVERSITY OF BATH		**Equipment Specification Sheet**	**02/05/2022**
		UNIT	DRUM DRYER
		UNIT ID	DD-01
		CLIENT	BANES CNCL
		MECH DRWNG	FIGURE 4.3 a,b,c
PREPARED BY	A. RANERI	**UNITS**	METRIC
PLANT	The New Whey Ltd.	**PROCURED BY**	BANES CNCL
LOCATION	Ditcheat, Somerset	**INSTALLED BY**	ENG. CONSULTANT
GENERAL			
TYPE	SINGLE DRUM DRYER		
OPERATION	PLASTIC MAKING		
SERVICE	Production of Dried Plastic Flakes through Evaporation		
DRUM LENGTH	3000 mm	**DRUM DIAMETER**	1250 mm
UNIT LENGTH	3400 mm	**UNIT HEIGHT**	4115 mm
UNIT WIDTH	1490 mm	**UNIT VOLUME**	20.85 m³
DRYING SURFACE AREA	11.78 m²	**DRUM HEART LINE**	3250 mm
APPLICATOR ROLL DIAMETER			240 mm
APPLICATOR ROLL NUMBER			4 -
TOTAL WEIGHT	21.58 tonnes		
PROCESS DATA			
BIOPLASTIC	**INLET**	**OUTLET**	
Mass Flowrate	3.81	2.515 tonnes batch^{-1}	
Temperature	25	72 °C	
Pressure	1.013	1.013 bar	
STEAM	VAPOUR PHASE	CONDENSATE PHASE	
Mass Flowrate	4.249	4.249 tonnes batch^{-1}	
Temperature	140	106.8 °C	
Pressure	3.612	1.013 bar	
BATCH TIME	6 hours		
POWER REQUIREMENT	33 to 60 kW		
CONSTRUCTION AND MATERIALS			
DESIGN TEMPERATURE	314 °C	**DESIGN PRESSURE**	3.973 bar
DRUM MATERIAL	**THICKNESS**	**DRUM WEIGHT**	779.1 kg
STEEL DRUM with CHROMIUM COATING (8.5 mm)			
AISI 4140	8.3 mm		
Chromium	0.2 mm		
APP. ROLL MATERIAL		**APP. R. WEIGHT**	29.66 kg
STEEL ROLLS with CHROMIUM COATING (8.5 mm)		**APP. R. LENGTH**	3000 mm
AISI 4140	1.5 mm		
Chromium	0.2 mm		
KNIFE MATERIAL	AISI M7	**KNIFE WEIGHT**	7.928 kg
KNIFE LENGTH	3020 mm	**KNIFE WIDTH**	2 mm
KNIFE HEIGHT	165 mm		
K. HOLDER MATERIALS	ALUMINIUM, COMPOSITES	**K. HOLD. WEIGHT**	318 kg
VAPOUR HOOD MAT.	AISI 304	**V. HOOD WEIGHT**	38 kg
MAIN FRAME MAT.	AISI 4140	**M. FRM. WEIGHT**	20,320 kg
DRUM WELDING	SEAMLESS		

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Appendices

Unit Design appendices are labelled as 'A', whereas Mechanical Engineering Design appendices are labelled as 'C'.

Appendix A1

$$\Delta T_{lm} = 74.67°\text{C} = \frac{(140°\text{C} - 72°\text{C}) - (T_{h,o} - 25°\text{C})}{\ln\frac{(140°\text{C} - 72°\text{C})}{(T_{h,o} - 25°\text{C})}}$$

$$T_{h,o} = 106.8°\text{C}$$

Appendix A2

Material and energy balances were solved using the centred finite difference approach:

$$\frac{D_{we}Ld\alpha\rho}{R_2}\frac{\partial^2 X}{\partial\theta^2} - \frac{M}{1000}R_2L\xi \times MTR = 2\pi V_{rc}LdR_2\alpha\rho_s\frac{\partial X}{\partial\theta}$$

$$a\frac{\partial^2 X}{\partial\theta^2} + b\frac{\partial X}{\partial\theta} + \sigma = 0$$

Where $a = \frac{D_{we}Ld\alpha\rho}{R_2}$, $b = -2\pi V_{rc}LdR_2\alpha\rho_s$, $\sigma = -\frac{M}{1000}R_2L\xi \times MTR$

$$a\frac{X_{i-1} - 2X_i + X_{i+1}}{\Delta\theta^2} + b\frac{X_{i+1} - X_{i-1}}{2\theta} + \sigma = 0$$

$$\phi X_{i-1} - 2aX_i + \omega X_{i+1} = \gamma$$

Where $\phi = a - \frac{b\Delta\theta^2}{2\theta}$, $\omega = a + \frac{b\Delta\theta^2}{2\theta}$, $\gamma = -\Delta\theta^2\sigma$

Giving the following matrix equation for material balances:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \phi & -2a & \omega & 0 & 0 & 0 & 0 & 0 \\ 0 & \phi & -2a & \omega & 0 & 0 & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \phi & -2a & \omega \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} X_0 \\ X_1 \\ X_2 \\ \vdots \\ X_{N-1} \\ X_N \end{bmatrix} = \begin{bmatrix} X_i \\ \gamma \\ \gamma \\ \vdots \\ \gamma \\ X_f \end{bmatrix}$$

For energy balances:

$$\frac{kLd}{R_2}\frac{\partial^2 T}{\partial\theta^2} + k_dR_1L\frac{T_B - T}{\Delta x} - hR_2L(T - T_{air}) - \frac{M}{1000}R_2L\xi C_{pw}T \times MTR = 2\pi V_{rc}C_pLdR_2\rho\frac{\partial T}{\partial\theta}$$

$$\eta\frac{\partial^2 T}{\partial\theta^2} + \lambda\frac{\partial T}{\partial\theta} + cT + \psi = 0$$

Where $\eta = \frac{kLd}{R_2}$, $\lambda = -2\pi V_{rc}C_pLdR_2\rho$,

$\psi = k_dR_1L\frac{T_B}{\Delta x} + hR_2LT_{air}$, $c = -\left(\frac{k_dR_1L}{\Delta x} + hR_2L + \frac{M}{1000}R_2L\xi C_{pw} \times MTR\right)$

$$\eta\frac{T_{i-1} - 2T_i + T_{i+1}}{\Delta\theta^2} + \lambda\frac{T_{i+1} - T_{i-1}}{2\theta} + cT_i + \psi = 0$$

$$\varepsilon T_{i-1} + (c - 2\eta)T_i + \kappa T_{i+1} = -\psi$$

Where $\varepsilon = \eta - \frac{\lambda\Delta\theta^2}{2\theta}$, $\kappa = \eta + \frac{\lambda\Delta\theta^2}{2\theta}$

Giving the following matrix equation for energy balances:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \varepsilon & c-2\eta & \kappa & 0 & 0 & 0 & 0 & 0 \\ 0 & \varepsilon & c-2\eta & \kappa & 0 & 0 & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \varepsilon & c-2\eta & \kappa \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} T_0 \\ T_1 \\ T_2 \\ \vdots \\ T_{N-1} \\ T_N \end{bmatrix} = \begin{bmatrix} T_i \\ -\psi \\ -\psi \\ \vdots \\ -\psi \\ T_f \end{bmatrix}$$

Appendix A3

Moisture diffusivity in element calculations, based on Kanevce et al. (2003), for initial and final moisture content:

$$Diffusivity = 9 \times 10^{-12} \times X^{-2} \times \left(\frac{T}{303}\right)^{10}$$

$$Diffusivity_{initial} = 9 \times 10^{-12} \times 0.6667^{-2} \times \left(\frac{298}{303}\right)^{10} = 1.714 \times 10^{-11}$$

$$Diffusivity_{final} = 9 \times 10^{-12} \times 0.1^{-2} \times \left(\frac{345}{303}\right)^{10} = 3.296 \times 10^{-9}$$

$$Average = \frac{1.714 \times 10^{-11} + 3.296 \times 10^{-9}}{2} = 1.657 \times 10^{-9}$$

Appendix A4

At room temperature and pressure, 1 mol of air takes up 24L:

$$c_{air} = \frac{1mol}{0.024m^3} = 41.67mol\ m^{-3}$$

Appendix A5

Various wall thicknesses were calculated from different equations. From Engineers Edge (2022):

$$t_c = 8.5mm = 0.3346inch$$

$$S = \frac{D_1 P}{2t_c} = \frac{48.54inch \times 52.39psi}{2 \times 0.3346inch} = 3800psi$$

This value is considerably lower than the values presented by Engineers Edge (2022).

$$P = 52.39psi < 0.385SE$$

$$t_c = \frac{52.39psi \times 24.27inch}{3800psi - 0.6 \times 52.39psi} = 0.3374inch = 8.57mm$$

This is the thickness required to handle circumferential stress. The thickness required to handle longitudinal stress is given by Raheja (2019), for $P \leq 1.25SE$:

$$t_c = \frac{PR_1}{2SE + 0.4P} = \frac{52.39psi \times 24.27inch}{2 \times 3800psi + 0.4 \times 52.39psi} = 0.1668inch$$

Thus, the thickness required against circumferential stress is sufficient for longitudinal stress.

$8.57mm > 8.5mm$; wall thickness, according to this calculation, must be increased.

Alternatively, for low-pressure cylinders (Engineers Edge, 2022), where the addition of 0.3 inches accounts for metal thickness variations:

$$t_c = \frac{PD_1}{2500} + 0.3 = \frac{52.39psi \times 48.54inch}{2500} + 0.3inch = 1.317inch = 0.03345m$$

According to this calculation, $33.45mm$ is required to withstand the pressure; if inner diameter is kept constant, outer diameter required would be:

$$D_2 = 1.233m + (0.03345m \times 2) = 1.3m$$

The calculation without accounting for metal thickness variations (assuming thickness is exact):

$$t_c = \frac{PD_1}{2500} = 1.017inch = 0.02583m;\ D_2 = 1.285m$$

In both of these cases, outer diameter is greater than the designed 1.25m. The thickness of the metal was too great, the MATLAB script demonstrated that outlet plastic temperature was not achieved. Reduction of inner diameter to 1.183m, with outer diameter constant 1.25m did not solve the issue.

Appendix A6

```
for j = 1 : N+1
   if j<7 % FIRST PERIOD
       d(1,j) = d_0.*((Rho_f-Rho_w)./(Rho(1,j)-Rho_w)); % volume element
thickness
       Xi(1,j) = 1; % evaporation rate ratio, [-]
       if j<2
         T_B(1,j) = T_B0-10/6; % internal surface temperature of cylinder,
[K]
       else
         T_B(1,j) = T_B(1,j-1)-10/6;
       end
   elseif j<37 % SECOND PERIOD
       d(1,j) = d_0.*((Rho_f-Rho_w)./(Rho(1,j)-Rho_w));
       Xi(1,j) = 1;
       if j<22
         T_B(1,j) = T_B(1,j-1)-10/15;
       else
         T_B(1,j) = T_B(1,j-1)+5/15;
       end
   else % THIRD PERIOD
       d(1,j) = d(1,j-1); % element thickness is constant!
       Xi(1,j) = 0.9061;
       if j<69
         T_B(1,j) = T_B(1,j-1)+15/32;
       else
         T_B(1,j) = T_B(1,j-1);
       end
   end
end
```

Appendix A7

```
% The coefficients of the first row of the matrix
LHS(1,1) = 1;
% Setting other non-zero elements
for i = 2 : N
   LHS(i,i-1) = Phi(1,i);
   LHS(i,i) = -2*a(1,i);
   LHS(i,i+1) = Omega(1,i);
end
% The coefficients of the last row of the matrix
LHS(N+1,N+1) = 1;
% Setting RHS values
RHS(1) = X_i;
```

```
for jj = 2 : N
   RHS(jj) = Gamma(1,jj);
end
RHS(N+1) = X_f;

u = LHS\RHS;
```

Appendix C1

Expansion effects are calculated as follows. Knife expansion considers temperature rise due to friction. For the AISI 4140 in the drum:

$$\Delta L = \alpha_{expansion} L \Delta T$$

$\alpha_{expansion} = 12.2 \times 10^{-6} K^{-1}$ (AzoMaterials, 2019)

$$\Delta L = (12.2 \times 10^{-6} K^{-1})(0.0083m)(130 - 25℃) = 10.63\mu m$$

For the chromium coating, where expansion coefficient is taken from EduPack (2009):

$$\Delta L = (6.5 \times 10^{-6} K^{-1})(0.0002m)(130 - 25℃) = 0.1365\mu m$$

For the knife, $T_{final} = 13.09 + 25 = 38.09℃$:

$$\Delta L = (11.55 \times 10^{-6} K^{-1})(0.165m)(38.09 - 25℃) = 24.95\mu m$$

Appendix C2

As three batches are performed per day:

$$\Delta L = -62.1\mu m\ per\ day$$

Knife requires replacement once length reaches 100 mm, thus after a reduction of 65 mm.

$$\frac{65}{0.0621} = 1047 \approx 3\ years\ of\ usage$$