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Applied Mathematical Model for Solar Energy Collection and Thermal Storage

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Abstract: *Solar thermal storage systems (STSS) are renewable energy systems that provide a continuous, controllable source of heat for many applications. The inherent variability of solar insolation poses a challenge to the use of direct solar power for continuous operations. A dynamic non-linear model of the STSS was initialised via a steady state analysis and verified by drying 1000 kg of cocoa beans per batch from 60% to 8% moisture content. Ambient temperature and insolation data for Trinidad in 2017 were used as inputs. This was achieved by modifying flow rates, varying aspect ratio of the storage tank, and observing their effect on storage tank temperature profiles and drying air temperatures. The steady state analysis determined the tank volume as 12.57 m*^{3} *and a required mass airflow rate of 1020 kg/h. A dynamic model of the STSS revealed an optimal tank aspect ratio of 2:4 m (D: H) and that three AE-40 solar collectors were sufficient. The effect of the circulation rate between the storage tank and solar collectors on energy storage was found to be negligible. The need for temperature control was demonstrated and a control strategy developed. A pilot plant was built using recommended specifications, albeit without temperature control. As predicted, drying was more than sufficient, but poor control led to burnt cocoa beans. The application of this work extends well beyond the cocoa bean test case, and the open-source models built can be applied to optimise the design of any solar heating application.*

Keywords: *Solar thermal, drying, simulation, optimisation, Aspen*

1. Introduction

Solar thermal storage systems (STSS) are used to collect energy from solar radiation, store that energy via a thermal fluid, and then discharge it in a controlled manner. The typical components in STSS include solar collectors with insulated storage tank, blower, pump, and heat exchanger, as well as other minor components (Fan and Furbo, 2012; Han et al., 2009). The STSS are a common technology used in heating systems in temperate climates and also provide an interesting solution to the limitations of conventional dryers (Bal, Satya, and Naik, 2010).

Thermal energy can be stored in high thermal capacity fluids or solids as a change in internal energy of a material as sensible heat, latent heat, chemical or any combination of these. In sensible heat storage, thermal energy is stored by raising the temperature of a solid or liquid, utilising the heat capacity and change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat capacity of the medium, the temperature change, and the amount of storage material (Fan and Furbo, 2012; Han et al., 2009).

STSS represent a significant capital investment that is off-set by the reduction in operating costs over the lifetime of a project. The proper design and sizing of STSS components will be a determining factor in the economic feasibility of STSS installations. To do this sizing properly one must consider thermo-physical effects that are driven by fluid dynamic considerations such as stratification of fluid in the storage tanks, which is governed by the Boussinesq approximation applied to the Navier-Stokes equations and the accurate modelling of the radiative, conductive, and convective heat transfer, as well as momentum transfer that occurs in the solar collector and stratified storage tank. This requires a finite element method to solve a set of simultaneous partial differential equations under time varying boundary conditions such as meteorological data for solar intensity, humidity, and ambient temperature (Bird, Stewart, and Lightfoot, 2002).

The stratified tank and solar collector are at the heart of STSS and require detailed investigation (Lutchman,

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2018). Stratification due to thermally driven density differences between layers of fluid in the tank is a naturally occurring phenomenon. The understanding of stratification is important as it affects the overall STSS efficiency. Hot fluid, which migrates naturally to the top of the tank, is optimal for providing energy for the load. Besides, cooler fluid from the bottom of the tank is optimal for sending to the solar collector as this improves collector efficiency (see Figure 1A). However, this must be balanced with cost of insulation, dimensions, especially the aspect ratio of the tank, and make-up fluid due to evaporative losses. Several authors have proposed models to describe the tank's operating characteristics (Fan and Furbo, 2012; Han et al., 2009).

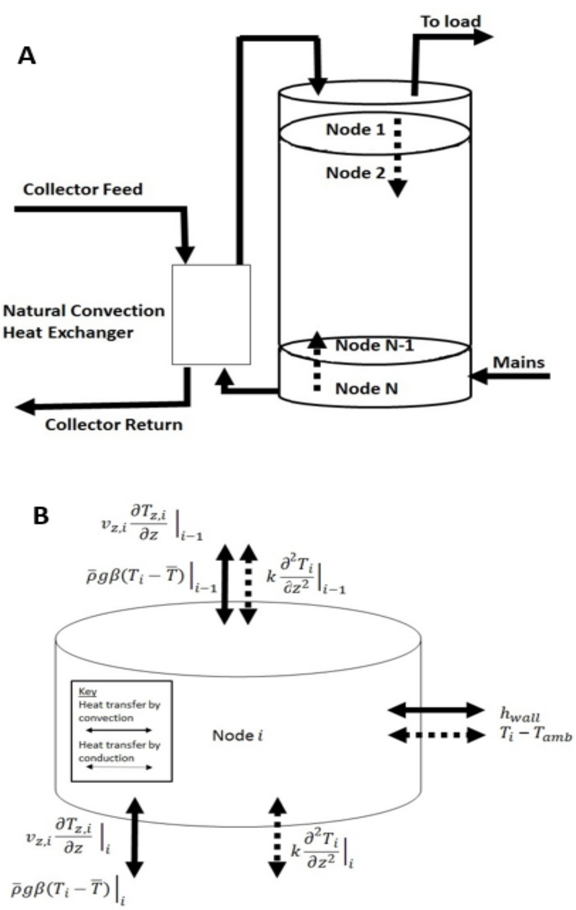

Figure 1. Stratified Tank Model in 1-Dimension

Solar collectors exist commercially and are used for the direct heating of a thermal transport fluid using solar radiation. Though several designs are available, the design chosen for this investigation was the all-glass vacuum tube model. This model has a very high efficiency for the conversion of solar insolation to thermal energy and several mathematical models have been proposed to describe the behaviour of these systems (Li et al., 2010; Amrizal et al., 2012). In Amrizal et al. (2012), the linearised mathematical model is limited because the effect of the physical factors such as natural convection and varying geometry cannot be determined analytically (Lutchman, 2018). The non-linear mathematical model by Li et al. (2010) does take into account those physical factors and was able to accurately predict the outlet temperature of the collector to within 2%. Applying the model from Li et al. (2010) using Aspen's Thermodynamic Property Package reduces the error to less than 2% because of the ability to update thermodynamic properties dynamically during simulations (Lutchman, 2018).

For complete reviews on STSS designs and uses, see Bal et al. (2010); Tian and Zhao (2013); and Tomar et al. (2017). This publication applies STSS to drying. Drying occurs via two simultaneous and related mechanisms. The first mechanism is the removal of moisture from the surface of the wetted solid by vaporisation. The rate at which vaporisation occurs is dependent on the relative humidity in the surrounding atmosphere (Perry and Green, 1997). The second mechanism, migration of internal moisture to the surface, is dependent on the solid's internal structure.

Efficient reduction of the moisture content of large quantities of bulk materials requires industrial-scale dryers. Factors that affect the selection and sizing of dryers include the quantity of material to be dried, the required moisture removal rate, and the change in moisture content. Other factors that must also be considered in the selection of a dryer include cost and the availability of space and utilities. Common types of industrial dryers are rotary, fluidised bed, rolling bed, conduction and convection dryers (Mujumdar, 2014). The more conventional dryer systems are plagued with issues such as lower efficiency of operation and problems controlling drying air flow and temperature, which result in inconsistent products (Mujumbar, 2014). Conventionally, they are powered with fossil fuels.

The example investigated in this paper is an application of STSS for drying fermented cocoa beans. The example of cocoa was chosen for two reasons: Trinidad and Tobago has over 200 years of production of fine quality cocoa (Bekele, 2003); and a preliminary pilot plant using a solar thermal storage system (although without a control system) has been built and tested on cocoa at the La Reunion Research Station in Trinidad and Tobago (Lutchman, 2018).

A fine cocoa is characterised by its fresh fruit flavour, ground fruit flavour, balance of bitterness and astringency, and its general appearance. Specifically, fine cocoa must have less than 1.67% mould present (Lasisi, 2014), less than 1.75% free fatty acids (Guehi et al., 2010), and a chocolate brown colour (Lasisi, 2014). Trinidad and Tobago has a classification of 100% fine cocoa fetching anywhere between USD 5,000-10,000/tonne (Nieberg, 2016). After fermentation, the cocoa beans have a water content of 50 to 60% (Lasisi, 2014, Guehi et al., 2010) that need to be reduced by drying to 6 to 8% (Lasisi, 2014). There are two main methods of drying cocoa: air-drying in sunlight, in which the crop is spread out and exposed to sunlight and the free flow of air; and forced heated air convection, in which enclosed drying frames expose the material to the forced flow of hot dry air that is produced by burning fuels. Each method has advantages and problems. Air drying is very labour intensive, dependent on consistent sunlight, takes up to 22 days (Lasisi 2014), has more limited scale-up potential, and can have issues with high mould percentages and vermin (Sukha, 2003).

Forced heated air convection is able to dry the greatest quantity of beans quickly with less labour and is readily scalable, but can produce poorer quality cocoa due to poor temperature control leading to hardening of beans, a higher percentage of free fatty acids, and poor final colour (Guehi et al., 2010, Sukha, 2003). In addition, often forced heated air drying requires either electrical heating or burning of diesel or natural gas. The burning of fuels for heating is typically done without a heat exchanger so beans are often exposed to flue gases (Sukha, 2003). A controllable heat source that reduces the dependency on fossil fuels is desirable as it would be more environmentally friendly, reduce contamination of the product, and, most importantly, allow for the provision of an adequate flow of air at an optimal temperature that removes instances of product damage due to air. The solar thermal storage system built as a pilot plant and simulated in this article addresses these concerns.

The work presented is a complete dynamic model built in Aspen Plus Dynamics where key pieces of equipment (stratified tank and solar collectors) are simulated in Aspen Custom Modeler. Steady state simulations were done to size individual components (Lutchman, 2018). Dynamic simulations were then used to determine the optimal aspect ratio of the tank, number of solar collector units needed, and to design a control strategy. Temperature control is required. If temperatures are excessive, this can lead to burning or case hardening of cocoa, making the cocoa unsellable (Sukha, 2003).

2. Modelling Basis

Overall Design and Steady State Analysis

The overall schematic is depicted in Figure 2. The system includes a solar collector, tank, blower, radiator, pump, and supplemental electric heater. The design basis for the steady state and dynamic simulations are listed in Table 1.

Steady state design provides the size of the storage tank, power requirement, and mass air flow rate (Sodha, et al., 1987). For complete details and calculations, see Lutchman (2018). Baseline conditions from the steady state system were used for the overall dynamic model and provided a limiting condition check for the dynamic simulation results.

Dynamic Models

To refine the system design, develop a control strategy, and account for variability in insolation and ambient temperature, a dynamic design was deemed necessary. To do the dynamic design, custom unit operations needed to be developed for the stratified tank and solar collectors.

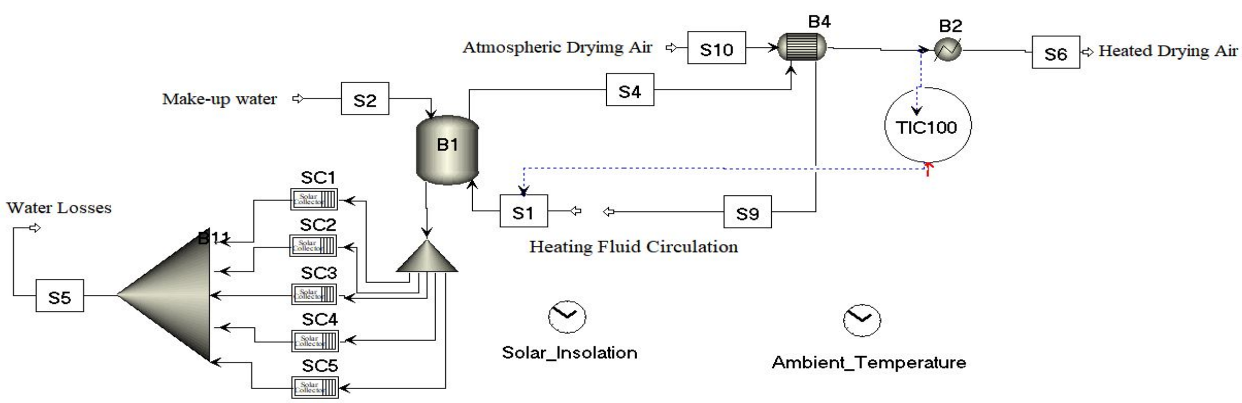

Figure 2. Dynamic Model of STSS

Table 1. Design Basis

Parameter	Value	Units
Mass of wet beans	1000	kg
Initial moisture content	60%	kg moisture/kg bean
Final moisture	8%	kg moisture/kg bean
Total drying time (t_{Dry})	120	Hours
Storage capacity time	48	Hours
Dryer exit air temperature	5	**ºC above dew point**
Maximum tank operating temperature	80	**ºC**
Tank temperature differential (ΔT)	20	**ºC**

Stratified Tank

Temperature gradients exist in the storage tank, and it is critical to model these to ensure that the actual temperature of fluid going to the radiator is correct, and will change with respect to time due to vertical position and charging/exiting flowrates. A one-dimensional model (see Figure 1A) was done using equations from Bird, Stewart, and Lightfoot (2002). Each vertical disk is assumed to be well mixed and uniform with heat transfer occurring at the boundaries of the disks (see Figure 1B) and by flow in and out of the tank. Heat convection and buoyancy are the primary forces. Heat losses to the walls of the tank and at the top of the tank are included and play a pivotal role in natural convection flipping layers, which occur at night.

Numerical solutions of the Navier-Stokes equations in two-dimensions may be used to predict the node temperatures and the velocity components of the flows but will require inclusion of surface tension in the water for proper predictions to occur (Lutchman, 2018).

A stratified tank model was built in Aspen Custom Modeler (ACM). The ACM model fits seamlessly into an Aspen Dynamics simulation where it is used to represent the stratified tank. Validation of the simulation model can be seen in Lutchman (2018).

Key assumptions of the models:

- Boussinesq Approximation: fluid density is assumed constant in the continuity equation and is allowed to vary in the momentum equations due to thermal expansivity.
- The mass water content of the ambient air is assumed to be constant.
- Other property constants assumed to not change significantly over range of operating conditions.
- All interconnected pipework is considered insulated with no heat losses.
- The system was modelled as a closed system; in practice evaporative losses occur.
- The top of the tank node contains ports for return from solar collector and supply to heat exchanger (see Figure 1A).
- The bottom of the tank node contains ports for supply to solar collector and return from heat exchanger (see Figure 1B).

The average density of water ($\underline{\rho}$) in the tank is found using Aspen properties using compositions, fluid, pressure (*P*), and average temperature ($\underline{T}$).

The following equations are used to describe the system. Tables 2 and 3 list the parameters used.

Net velocity of flow:

$$v_n = \frac{M_n}{\frac{\pi}{4} D^2 \underline{\rho}} \tag{1}$$

Motion Equations:

$$\underline{\rho}\frac{\partial v_{z,i}}{\partial t} + v_{z,i}\frac{\partial v_{z,i}}{\partial z} - \mu\frac{\partial^2 v_{z,i}}{\partial z^2} + \underline{\rho} g\beta(T_i - \underline{T}) = 0 \quad \text{for } i=1:N-1 \tag{2}$$

$$\underline{\rho}\frac{\partial v_{z,i}}{\partial t} + v_{z,i}\frac{\partial v_{z,i}}{\partial z} + \underline{\rho} g\beta(T_{z,i} - \underline{T}) = 0 \quad \text{for } i=N \tag{3}$$

Energy Equation:

$$\frac{\pi}{4} D^2 \underline{\rho} C_p \Delta z \frac{\partial T_{z,i}}{\partial t} + v_{z,i}\frac{\partial T_i}{\partial z} + k\frac{\partial^2 T_i}{\partial z^2} + \pi D h_{wall}\Delta z (T_i - T_{amb}) = 0 \quad \text{for } i=1:N-1 \tag{4}$$

Initial Conditions:

$$v_{z,i}(t=0) = v_n \quad \text{for } i=0:N \tag{5}$$

$$T_i(t=0) = T_{amb} \quad \text{for } i=0:N \tag{6}$$

Boundary Conditions:

$$v_{z,j}(t \geq 0) = v_n \quad \text{for } j=0 \tag{7}$$

Energy Balance on Top Node (j=0)

$$\frac{\pi}{4} D^2 \underline{\rho} C_p \Delta z \frac{\partial T_0}{\partial t} = F_{SC,in} R_{mm} C_p (T_{SC,in} - T_0) + F_{HX,out} R_{mm} C_p (T_0 - T_{HX,out}) \tag{8}$$

where,

$F_{SC,in}$ is molar flowrate into tank from Solar Collector
$T_{SC,in}$ is temperature of fluid from Solar Collector into tank
$F_{HX,out}$ is molar flowrate out of tank to Heat Exchanger
$T_{HX,out}$ is temperature of fluid out of tank to Heat Exchanger

Energy Balance on Bottom Node

$$\frac{\pi}{4} D^2 \underline{\rho} C_p \Delta z \frac{\partial T_N}{\partial t} = F_{SC,out} R_{mm} C_p (T_N - T_{SC,out}) + F_{HX,in} R_{mm} C_p (T_{HX,in} - T_N) \tag{9}$$

where,

$F_{SC,out}$ is molar flowrate out of tank to Solar Collector
$T_{SC,out}$ is temperature of fluid out of tank to Solar Collector
$F_{HX,in}$ is molar flowrate in to tank from Heat Exchanger
$T_{HX,in}$ is temperature of fluid into tank from Heat Exchanger

Table 2: Model Parameters Stratified Tank

Symbol	Value	Units	Definition
Β	6.9E-5	m^3/K	Thermal expansion
G	9.81	m/s^2	Acceleration due to gravity
C_p	4200	J/(Kg-K)	Specific heat of water
R_{mm}	18	g/mole	Molecular weight of water
K	0.58	W/(m-K)	Thermal conductivity of water
Μ	0.00092	Pa-s	Viscosity of water
h_{wall}	0.001	$kW/(m^2\text{-}K)$	Tank wall heat transfer coefficient

Table 3: Baseline Operating Conditions Stratified Tank

Symbol	Value	Units	Definition
Δz	0.05	M	Preferred height of each node
D	2.0	M	Tank diameter*
H	2.0	M	Tank height*
T_{amb}	303.15	K	Ambient temperature**

* Changes during aspect ratio study;   ** Changes with actual meteorological data

Table 4: Model Parameters Solar Collector

Symbol	Value	Units	Definition
W	1.80	M	Length of tube
N	32	--	Number of tubes
r_1	0.0185	M	Inner tube radius
$\tau\alpha_\theta$	0.837	--	Product of transmittance of outer tube and absorptance of coating at prevailing incident angle
U_L	0.85	W/(m^2-C)	Heat loss coefficient (Li et al., 2010)
C_p	4200	J/(kg-C)	Specific heat of water
A_1	Calculated	m^2	Cross sectional area of tube
A_2	3	m^2	Area of Absorber Surface
ε	0.5	--	Proportion of water hot in tube
μ	1	Cp	Kinematic viscosity
ρ	980	kg/m^3	Water density
γ	0.0000081	1/K	Thermal expansion coefficient
G	9.81	m/s^2	Gravitational acceleration
β	0.96	Radians	Tilt angle of collector
M	10	Kg	Mass charge of collector

Table 5: Baseline Operating Conditions Solar Collector

Symbol	Value	Units	Definition
M_{Flow}	0.139	kg/s	Mass Flow
$I_{t\theta}$	0 to 1,000	W/m^2	Solar Insolation*
T_{in}	303.15	K	Inlet Temperature
T_{out}	303.15	K	Outlet Temperature
T_{amb}	303.15	K	Ambient temperature*

* Changes with actual meteorological data

Solar Collector

In the Li et al. (2010) model, the heat transfer in the collector is composed of natural convection in a single glass tube and forced flow in the manifold header. An energy balance on a single tube was performed by Li et al. (2010) that considered both radiant sources and sinks as well as convection and conduction terms. Fluid flow equations include the friction and buoyancy in the tube.

By solving these equations, the inputs such as solar irradiation, inlet temperature and transport fluid flow rates are related to outlet conditions of pressure and temperature. The model assumes that the system operates with a single liquid phase. The accumulation of energy in the collector is equated to the energy gained by solar irradiation minus the energy lost to the surroundings. This model was selected and built in Aspen Custom Modeler. The results of Li et al. (2010) were replicated accurately and in some cases were slightly improved due to the more accurate thermodynamic properties package in Aspen (Lutchman, 2018).

The following equations were used to describe the solar collector. Tables 4 and 5 list the relevant parameters.

Pressure Drop Calculation

$$\frac{\pi}{4}r_1^2\Delta P - 2.0x10^{-8}\mu w M_{Flow} = 0 \tag{10}$$

Summation of manifold boundary conditions (Li et al., 2010):

$$kM_cC_p - 2I_{t\theta}\tau\alpha_\theta r_1 = 0 \tag{11}$$

$$M_{Flow}(T_{in} - T_{out}) - wkM_c + wk\varepsilon M_{Flow} - 2T_pM_{Flow} = 0 \tag{12}$$

Where k is a defined variable from Li et al. (2010) and M_c is natural circulation flow rate.

Convection flow rate equation (Li et al., 2010):

$$M_c\sqrt{0.002\varepsilon\pi\mu C_p} - \varepsilon\pi r_1^2\rho\sqrt{\beta g I_{t\theta}\tau\alpha_\theta r_1 w(sin(\beta))} = 0 \tag{13}$$

Overall energy balance for the solar collector (Li et al., 2010)

$$MC_p\frac{dT_p}{dt} - 3600\left(M_{Flow}C_p(T_{in} - T_{out}) + I_{t\theta}\tau\alpha_\theta A_2 - U_L\left(T_p - T_{amb}\right)A_1\right) = 0 \tag{14}$$

Where T_p is the mean temperature of the inlet and outlet water.

Using temperature, pressure and composition, the density, viscosity, and heat capacity are found using Aspen Properties package.

3. Simulation Method

Steady state

Steady state analysis was done in MS Excel 2016 and Aspen HYSYS v8.8 with flash drums as individual drying stages coupled to psychometric data. Drying loads to power requirements were calculated and designs were done for blower, pump, and radiator (Lutchman, 2018).

Dynamic

The dynamic simulations are run in the Aspen Dynamics (AD) V8.8 software and utilises standard and custom built components (stratified tank and solar collectors). Input functions for the solar insolation and ambient temperature were supplied using smoothed interpolation of entries in Aspen Dynamics' data input table blocks. Stream data such as flow, composition, temperatures, and pressures were initialised at the steady state conditions. The dynamic runs were broadly separated into two sets: the thermal charging of the stratified tank and the discharge of the tanks during drying runs. For the drying runs the temperature of the tank's nodes were initialised at the final values from the optimised thermal charging scenario. Code used for the base models can be found in Lutchman et al. (2019), and the control models can be found in Lutchman et al. (2021).

The finite element method applied in ACM was the backward differentiation formula setting (Tremblay and Peers, 2015). Numerical integration of the dynamic models was performed using a variable step nonlinear solver (4th order Runge-Kutta) that is built into the AD suite. The time dependent results for drying air temperature, solar collector outlet temperature, supplemental heater duty, and temperature controller output were then analysed using AD tools or output to Microsoft Excel and MathWorks MATLAB for presentation and analysis.

For all *in silico* experiments, solar insolation data was provided by Trinidad and Tobago Meteorological Office covering both Dry and Wet seasons. The average solar insolation was 204 W/m^2 to 187 W/m^2 for Dry versus Wet seasons with an ambient temperature of 26.6 °C to 27.4 °C. Properties of cocoa beans used here can be found in Ato Bart-Plange (2003) and Henderson (1984). For deeper insight into customising the model, see "How to Use the Simulation Tools" (Lutchman et al, 2021).

4. Results and Discussion

4.1 Steady State Analysis

Both the Air Mass Flow and Power follow a linear prediction model for varying Moisture Removal Rate (MRR) with goodness of fit, R^2 = 0.9986. The fitted equations are as follows:

$$M_{Air} = 215.07MRR - 3.5387 \text{ in kg/h} \quad (15)$$

$$P = 1.5049MRR - 0.0248 \text{ in kW} \quad (16)$$

Figure 3 shows the results from the steady state analysis of Moisture Removal Rate (MRR) versus requirements on Air Mass Flow (M_{Air}) and Power (P).

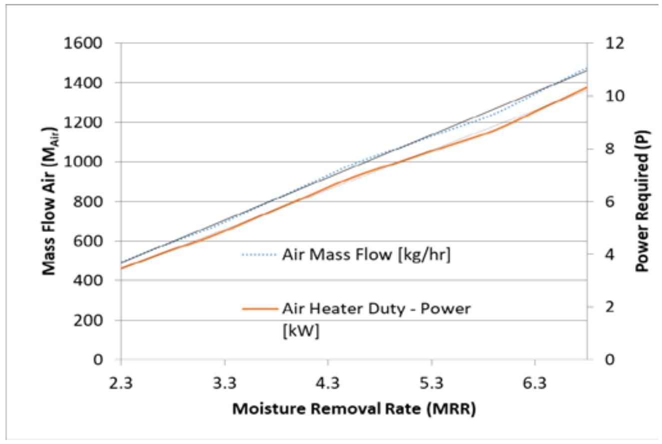

Figure 3. Sensitivity of Moisture Removal Rate on Mass Air Flow and Power Required

The steady state analysis provides scale up of the dryer depending on the amount of cocoa beans and their initial moisture content. It is also critical for testing the dynamic simulations on a limiting case. However, it does not consider the variability in solar insolation or ambient temperature; it uses a fixed efficiency for the solar collector and does not consider the geometry of the collector; and it uses a lumped parameter model of the tank and hence does not consider the stratification effects on air heater and collector performance. The rate of moisture removal was calculated as 4.3 kg/h. The steady state design determines the mass air flow rate (1020 kg/h) and tank volume (12.57 m^3), which form the basis of the dynamic simulation.

4.2 Dynamic Results

Aspect Ratio of Tank

The holding tank aspect ratio was varied between the limits 0.25 and 2.0 while keeping water circulation rate at 500 kg/h. As aspect ratio increases, the time to reach 60 °C decreases from 135 hours for 0.25 to 61 hours for 2.0 (see Figure 4). Likewise, the maximum temperature went from a low of 64 °C at 0.25 to water starting to boil at 61 hours for an aspect ratio of 2.0. There is heat loss from the tank top which is higher than heat loss through the insulated walls.

Hence, there is potential for natural convection flipping occurring at night with the top layer getting colder and then sinking to a lower level in the tank itself. Figure 5 demonstrates that with a taller and narrower tank the oscillations in temperature (due to natural convection flipping at night) decrease in magnitude.

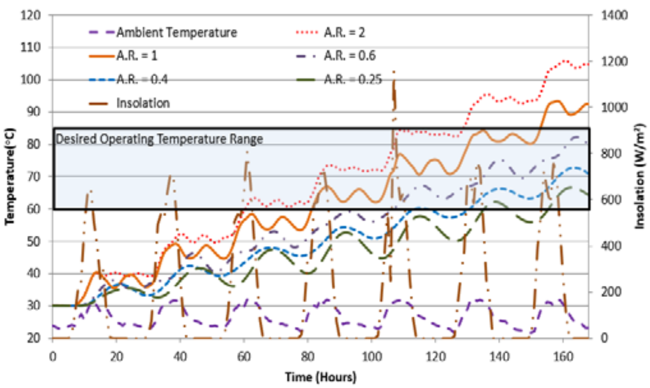

Figure 4. Effect of Aspect Ratio on Charging Using Trinidad Solar Insolation and Ambient Temperature Data for Wet Season

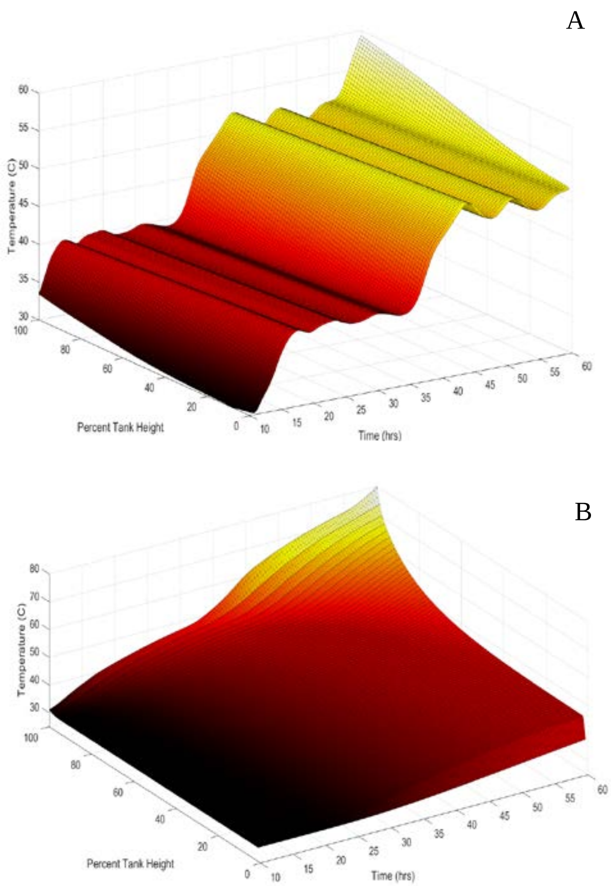

Figure 5. Tank Temperature Profile for One Dimensional Model

Tank Temperature Profile vs Solar Collector Circulation Rate

Large temperature differences can develop when hot water is added to the top of the tank and there is no mixing due to low flow down through the tank, when the circulation rate is 5 kg/h. In contrast, the scenario where the circulation rate is 500 kg/h shows a much lower temperature differential between the top and the bottom of the tank. However, it is clearly seen that the temperature of all the nodes rose steadily during the run (see Figure 5). This indicates that at low circulation rates, natural convection dominates, and at high circulation rates, forced convection dominates.

Number of Solar Collectors

Selecting the optimal number of collectors provides a balance between rapid recharge and matching the energy storage capacity of the tank. This must be done dynamically because insolation conditions and ambient temperatures can vary significantly. Too many collectors will result in high capital costs and loss of water from evaporation. The desired fluid temperature is between 60 to 85 °C. Temperatures higher than 85 °C will lead to the need for increased water replacement due to evaporation losses. Temperatures lower than 60 °C would not provide sufficient energy. It can be clearly seen in Figure 6 that to charge the tank to the desired temperature range, the optimum number of solar collectors is three during the wet season.

Performance during the wet season is not shown to be significantly worse than during the dry season. Although the solar insolation is approximately 10% less during the wet season, the ambient temperature is actually higher by a small amount (0.8 °C on average), and these factors seem to have net minimal effect on charging characteristics.

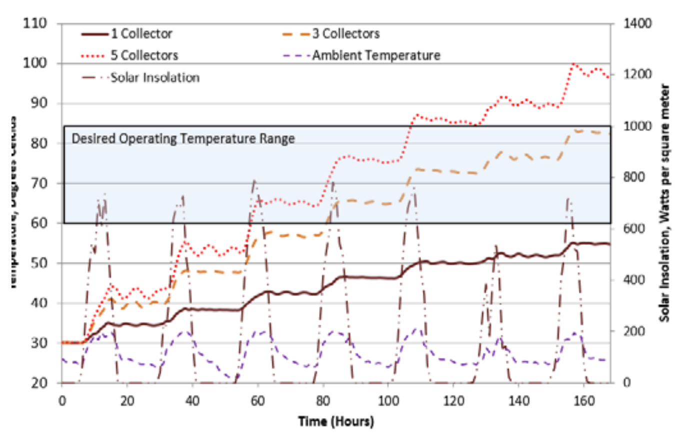

Figure 6. Varying Number Solar Collectors Using Trinidad Solar Insolation and Ambient Temperature Data for Wet Season

Solar Collector Loop Flow

In this test, the water circulation flow rate from the tank to the collector was varied between 400 and 700 kg/h. The supply of water from the tank to the heat exchanger is fixed. A higher circulation rate would mean that forced convection through the stratified tank would dominate natural convection effects (as governed by the Boussinesq approximation) (Bird et al., 2002). Thus, one should expect to see lower cycling of the temperature during the nightly cool down. The dominance of forced circulation over natural convection led to a more linear cooling of the tank during the night, with the amplitude of the cycles dropping from approximately 4 ºC at the lowest circulation rate (400 kg/h) to under 1 ºC at the highest flow rate (700 kg/h) (see Figure 7). However, varying the circulation rate had nearly no effect on the time taken for the tank to reach operating temperature.

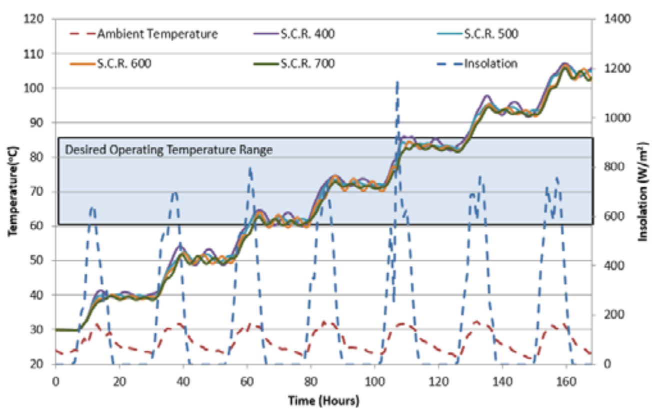

Figure 7. Varying Circulation Rate Using Trinidad Solar Insolation and Ambient Temperature Data for Wet Season

Proper Control on Dynamic System

Tight control in the drying of cocoa is essential. Higher temperatures can lead to product quality issues such as case hardening, which may result in moisture being trapped within the bean and potential fungal growth. Also, higher air temperatures result in premature drying in cocoa, and consequently under-developed flavour profiles. Figure 8 illustrates that the addition of the controller serves a dual purpose.

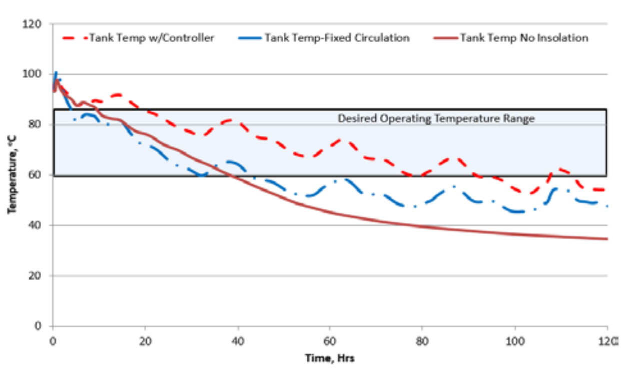

Figure 8. Inclusion of Proper Control on Discharge Temperature in Tank

Firstly, it can control conditions during times where the temperature of the tank is more than the desired drying air temperature (50 °C), and the produced drying air temperature is higher than that which is desired. Secondly, it prevents wastage of energy that results from overheating the drying air. Overheating is disadvantageous from an economic perspective. The energy store of STSS is a finite resource governed by the overall heat capacity of the storage media and the average temperature of said media. By not regulating the release of this energy, a precious commodity is wasted.

5. Conclusion

A novel dynamic non-linear model of the entire solar thermal storage system was developed and verified, using the drying of cocoa beans as an illustrative case study. Model results indicated the following:

- Aspect ratio of the tank should be 2.0;
- At low circulation rates, natural convection dominates forced convection and at high flow rates, forced convection dominates;
- Three solar collectors should be used in both wet and dry seasons;
- Circulation rate had little to no significant effect on the time taken for the system to reach operating temperature; and
- A temperature controller should be used to optimise consumption.

The final design for producing dried cocoa beans with a moisture content of 8% by weight from 1000 kg of fermented cocoa beans at 60% initial moisture content requires a holding tank (2 m in diameter and 4 m tall) and 3 AE-40 Solar Collector Units. Radiator and air blower sizes were also calculated, but not shown (Lutchman, 2018).

By combining the models of the solar collector (Li et al., 2010) and the stratified tank (Han et al., 2009), this model predicts behaviour that was not reported in previous publications such as the natural convection flipping that occurred at night in the storage tank. This is due to the fact that the stratified tank models found in the literature (Han et al., 2009) had not been coupled with a solar collector in a closed loop. Thus, the effect of energy flow into the system by convection and the relative influences of forced and natural convection were absent. It is the coupling of the stratified tank and the solar collector bank which allows for the mathematical prediction of this non-linear behaviour.

A pilot plant in Trinidad has been built, albeit without temperature control in place, and confirmed qualitatively the following (*personal communication*): prediction for total temperature, radiator design is sufficient, solar collectors and tanks correctly sized. As predicted by this work, absence of the controller led to excessive temperatures, which resulted in cocoa beans burning.

Although a detailed Life Cycle Analysis is beyond the scope of this work, it is worth noting the potential CO_2 savings from fossil fuel usage. The processing of a 1000 kg batch of wet cocoa beans uses 7 kWh of power for up to 120 hours. This produces 130 kg of CO_2 emissions if natural gas is the fuel source used and 180 kg of CO_2 if diesel is the fuel combusted. Thus, one drying plant over the course of 1 year could produce 7.8 MT or 10.8 MT of CO_2 for natural gas and diesel, respectively. All of these emissions can be avoided if a controlled solar thermal storage system is used to power the drying process.

The application of this work extends well beyond the cocoa bean test case, and could prove more useful to temperature climates. The models generated for this project in Aspen can be applied to optimise the design of various solar powered heating applications under any given atmospheric conditions (temperature, humidity, and solar insolation). This can be achieved by modifying system inputs, parameters, and the thermal fluid within the model (Lutchman et al, 2021).

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