ASM Sc. J., 13, Special Issue 4, 2020 for NCAFM2018, 104-112

Analysis on the Effect of Intermittent Ventilation in Solar Drying using CFD Simulation

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Intermittent drying was a proven method able to minimize the energy consumption in the drying process. In this study a large scale solar dryer was developed with intermittent ventilation technique to minimize the energy usage, but at the same time increasing the drying rate. The ventilation interval was defined by setting blower "on" and "off" function based on the maximum and minimum temperature of the water from the solar collector. CFD simulation tools were used to analyze the effect of different ventilation interval on the temperature of the dried product. CFD simulation results were compared and validated with the experimental data before it was used further in the analysis. The simulation results show that different temperature interval and range produce a different temperature profile inside the dried product. Compare to continuous ventilation, besides lower energy consumption, intermittent ventilation with blower "on" when water temperature interval between 60°C to 85°C produce the highest temperature inside the product. This interval also produces a more uniform product temperature for a product located at different locations in the drying chamber.

Keywords: CFD simulation; intermittent drying; large scale; optimization; ventilation

I. INTRODUCTION

Drying process requires a large amount of energy and consume up to 25% of the total energy used in the industry. Unfortunately, the heat efficiency of the drying process was only between 20-25% (Chua *et al.*, 2001). Various different techniques have been studied by researchers to minimize the energy consumption for drying process in the industry. Intermittent drying is among the commonly used methods other than integrating drying technology with heat pump system and recycling waste heat for drying purposes. Intermittent drying was performed by changing one or more factors that affects the drying rates such as airflow, drying air temperature, humidity, pressure, or heat input mode. Through this method, the operating conditions in the drying process are controlled with the aim of reducing operating costs

Previous studies have proven that among the advantages of drying intermittently over drying continuously is that it can reduce energy consumption (Kumar *et al.*, 2014). Studies by Kowalski & Pawlowski 2011 found that intermittent drying by changing the temperature of the drying air periodically between 100°C and 40°C on cylindrical kaolin decreases energy consumption of about one third compared to the constant drying conditions. This study also shows that the energy efficiency which is the net energy ratio used to cool one unit of moisture to the total energy used for the whole process was 1.92% for drying with intermittent ventilation and 0.7% for drying with intermittent moisture. Further study of intermittent drying of kaolin clay was conducted by Putranto *et al.* (2011) considering the impact of the reaction engineering approach used by considering the uniform temperature profile in the product. More accurate results are obtained where intermittent drying saves energy up to 48 and 61% compared to 50 and 67% by conventional dryers for varying temperature and humidity respectively. Yang *et al.* (2013) conducted a study on the effectiveness of drying with intermittent heat pumps on energy consumption, drying time, and moisture distribution for drying of Chinese cabbage seeds. The results of this study found that

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compared to conventional drying methods, the energy consumption rate was reduced by 48%.

Solar drying is naturally a type of intermittent drying because of sunlight conditions that can only be obtained during the day. In this study, a large-scale solar dryer with active ventilation was developed for sericite mica drying. Current methods of sericite mica drying using passive greenhouse dryer was time consuming and not efficient. The new solar dryer was developed to increase the drying rate of the sericite mica but at the same time need to minimize the operating cost. Active ventilation solar drying methods have been proven by earlier researchers to be more effective than passive ventilation. However, active ventilation requires higher costs as they require additional energy and equipment for ventilation. Therefore, to minimize the energy consumption rate during the drying process, intermittent ventilation methods are used. This method is selected based on the advantages that can be obtained from intermittent drying which has been proven by previous research as described above. For the developed solar dryer, the blower is the equipment that produce the ventilation. Intermittent ventilation was created when blower is functioning based on the temperature of the water in the circulation pipes. The blower switch "on" only for a certain time interval based on the selected water temperature range. This temperature range effects the condition in the drying chamber and the electricity usage by the blower. The small temperature range will minimize the use of electricity by the blower but at the same time the effect of the hot water system from the evacuated tube solar collector will be under-utilized. Whereas a larger temperature range will maximize the effect of hot water systems from evacuated tube solar collectors but high energy consumption from the blower is expected. Therefore, the study was carried out to determine the best temperature range that fully utilized the hot water effect from the evacuated tube solar collectors and at the same time minimize the use of electricity energy by the blower.

Apart from different temperature interval, the temperature range or span also affects the energy consumption rate by the blower as well as the temperature in the drying chamber. Temperature span means the difference between minimum and maximum temperature where the blower turns on. A small temperature range will cause higher repetition between blower "on" and "off" and it may cause faster wear and tear that leads to higher maintenance cost compare to bigger temperature range. However, the small temperature range can ensure that the temperature in the drying chamber is maintain higher and less electrical energy usage by the blower than the bigger temperature range.

In this study the computational fluid dynamics (CFD) simulation was used to analyse the effect of the different thermal liquid i.e. water temperature range and interval settings on sericite mica temperature during the drying process. Different water temperature range and interval setting will produce different intermittent ventilation pattern. Many researchers and scientists have used CFD simulation methods for solar drying development especially in the optimization of dryer design. The increasing trend in the use of CFD simulation method is due to its advantages over experimental methods. Among the studies that used CFD methods was a study by Mathioulakis *et al.* (1998) in the development of dryers for drying fruits. In this study, the Fluent software was used to predict the air velocity in the drying chamber to optimize the condition and performance of the dryer. The study conclude that the air velocity data and drying rates obtained from CFD simulation showed a good correlation with the drying tests result. The Fluent software has also been used by Amjad *et al.* (2015) to predict the air circulation in the drying chamber for a potatoes dryer. Air velocity results for simulation and experiments show a good correlation with a correlation coefficient of 87%. Suhaimi *et al.* (2013) also have conducted a study to predict drying uniformity in tray type dryer using fluent software. The study had shown that the CFD simulation can accurately show the airflow profiles in the drying chamber. This study also proves that the appropriate tray arrangement method can improved the airflow uniformity and indirectly increased the drying rate in the drying chamber.

From the above mentioned studies it shows that the main advantage of the CFD simulation method compared to the field experiment in evaluating the drying system is its ability to quickly study the effect of geometric changes and the flexibility to change the design parameters without the cost of expensive hardware changes. Furthermore, the information obtained from the CFD simulation results is more detailed and gives the researchers a clearer understanding of the changes or effects of each design change made and a better understanding of the performance of the dryer than the laboratory or field experiments.

Therefore, the objective of the study is to analyse the effect of different thermal liquid i.e. water temperatures interval and range on the temperature of the dried product for the newly developed large-scale solar dryer using CFD simulation.

II. MATERIALS AND METHODS

A. Solar Dryer System

The developed solar drying system consists of several main components namely evacuated tube solar collector, heat exchanger, blower, drying chamber and the controller. Water was used as a thermal liquid in the system. Evacuated tube solar collector absorbs heat from the sun and transfer the heat to the water passing through it. The hot water was then flow through the heat exchanger and the heat was transferred to the surrounding air and the blower will blow the hot air into the drying chamber. Water with lower temperatures from the heat exchanger will flow back to the evacuated tube solar collector and the same process repeated. Figure 1 shows the schematic diagram of the drying system developed. Figure 2 shows the actual drying chamber of the system. The developed system can accommodate up to 10 pallets of sericite mica with the drying chamber size of 1.25 m height x 1.7 m width x 16.4 m length.

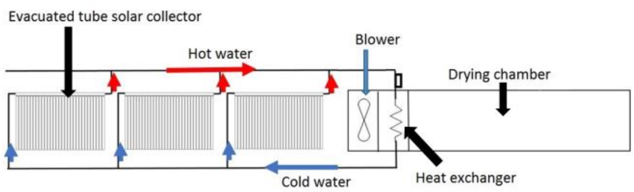

Figure 1. Schematic diagram of the new solar dryer

Figure 2. Drying chamber that can accommodate up to 10 pallets of sericite mica

The controller with control panel was used to control the blower operation. It was depending on the temperature of the water from the evacuated tube solar collector. The blower will switch "on" only if the temperature of the water from the evacuated tube solar collector reaches the maximum temperature. When the blower turns on, the water temperature will decrease, and the blower will stop when the water temperature drops to the minimum temperature. The value of maximum and minimum temperature was sets in the control panel. When the blower stops operating, the water temperature in the distribution pipe will increase again. The blower will be switched "on" again when the water temperature in the pipe reaches the maximum temperature and the same process will be repeated. This setting creates an intermittent ventilation to the overall drying process. The results from the initial experiment was compared to the CFD simulation results to validate the CFD model.

In this study, the CFD simulation was used to study the effect of different temperature interval on the sericite mica temperature in the drying chamber. Three different temperature settings were selected as shown in table 1. To determine the boundary condition at the inlet of the drying chamber in CFD simulation, without load field experiment was carried out for a period of 6 hours from 10.00 am to 4.00 pm for each interval and range during the clear sunny day to see the pattern of the blower function. Temperature, humidity and airflow sensors were placed in the drying chamber and data was recorded for every minute. The data was recorded in shorter time intervals to ensure that the blower "on" "off" pattern was captured accurately. Figure 3 shows the schematic diagram of sensor location used in the study.

Table 1. Different temperature interval and range analysed in the study

Interval	Minimum water temperature (°C)	Maximum water temperature (°C)	Temperature range (°C)
A	60	85	25
B	70	95	25
A1	70	85	15

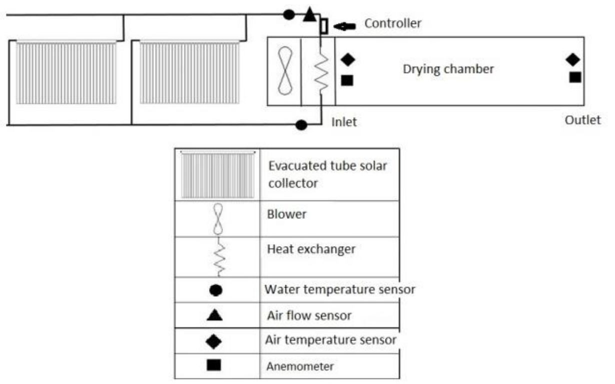

Figure 3. Sensors location

B. CFD Model Development

For this study a 3-dimensional (3D) model was used instead of a 2-dimensional (2D) model due to the accuracy of the simulation results (Suhaimi *et al.*, 2014). The 3D model for sericite mica and pallets was created using Solidworks software. The 3D model was then imported into the ANSYS Fluent Design modeler software and the domain for the drying chamber was created. To simplify the simulation process, the entire sericite mica layer was represented by a cylinder with its height being the total thickness of all the layers of sericite mica in one stack. The overall 3D model consists of 10 pallets arranged in parallel along the drying chamber. Sericite mica was arranged on a palette and each pallet can accommodate 4 stacks of sericite mica. Each stack consists of 15 layers of mica sericite. Figure 4 shows the actual arrangement in the drying chamber (left hand side) and in the form of 3D model (right hand side). Figure 5 shows the overall 3D model for CFD simulation.

Figure 4. Actual arrangement and 3D model of the sericite mica

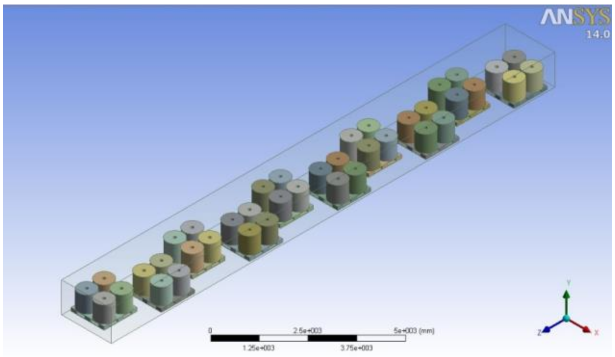

Figure 5. Overall 3D model for CFD simulation.

This 3D model was then meshed using the ANSYS ICEM CFD software. The unstructured tetrahedral mesh was used in this study. Table 2 shows the settings used for CFD simulation and table 3 shows the materials properties used in this simulation. To simplify the CFD simulation, the assumptions made are as follows:

1) Sericite mica was a solid material
2) The initial temperature and humidity content in the sericite mica were uniform
3) The initial temperature inside the drying room was uniform.

The data obtained from without load experiments were used as a boundary condition input value at the drying chamber inlet in the CFD simulation. User Define Function (UDF) of the boundary condition was used to simulate the changing inlet condition with time throughout the drying period.

Table 2. CFD simulation settings

Parameter	Setting
Cell zone condition	
Sericite mica	Solid - material (sericite mica)
Pallet	Solid – material (wood)
Drying domain	Fluid – material (air)
Analysis type	Transient
Gravity	$-9.81\ ms^{-1}$
Turbulence model	standard k-ε
Solar loading	
longitute	101.97
Latitude	4.2
Time zone	+8
Solar direction	Data from solar calculator
Initial condition	
Drying chamber temperature	33ºC
Sericite mica temperature	29ºC
Boundary condition	
Inlet type	velocity-inlet
Velocity	$3.0\ ms^{-1}$
Inlet temperature	*user define function file (udf)*
Outlet type	pressure-outlet = 0
Top wall of drying chamber	Semi transparent, *no slip wall* Solar radiation at negative – y direction, Radiation model- DO (*discreet ordinate*).
Side wall of drying chamber	Semi transparent, no slip wall ,adiabatic
Floor of drying chamber	no slip wall, fix temperature
Solution methods	SIMPLE (*semi-implicit pressure linked equation*)
Momentum	2nd order Upwind
transient formulation	1st order implisit
Solution control	
Pressure	0.3
Density	1
Body force	1
Momentum	0.7
turbulence kinetic energy	1

Table 3. Material properties used in the simulation

	Sericite mica	Pallet	Polycarbonate	Air
Density (kg/m^3)	2820	700	1190	1.225
Thermal conductivity (W/m.k)	0.35	0.17	0.2	0.0242
Specific heat (J/kg.k)	880	2310	1100	1006.43

For CFD simulation validation purposes, the results obtained from CFD simulation were compared with data obtained from field experiments at point 1 and 2 as shown in figure 6. The parameters compared were the temperature and velocity of the air in the drying chamber at point 1 and the temperature inside the sericite mica at point 2.

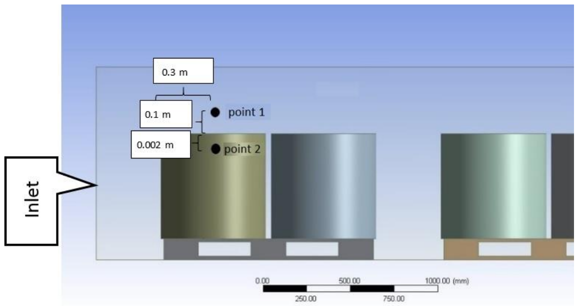

Figure 6. Position of point 1 and 2

III. RESULTS AND DISCUSSION

A. *CFD Model Validation*

Before the CFD model used further in the analysis process, the CFD simulation results was validated by comparing with the experimental results. Figure 7, 8 and 9 show the results of the simulated and experimental data for the temperature and velocity of the air in the drying chamber at point 1 and the temperature inside the sericite mica at point 2

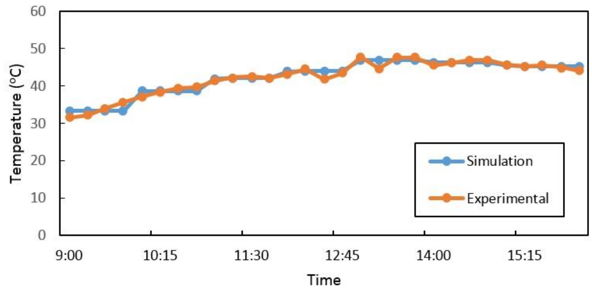

Figure 7. Drying chamber temperature at point 1 for simulated and experimental

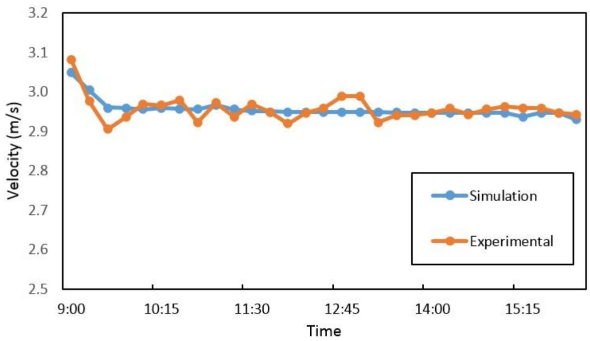

Figure 8. Drying chamber air velocity at point 1 for simulated and experimental

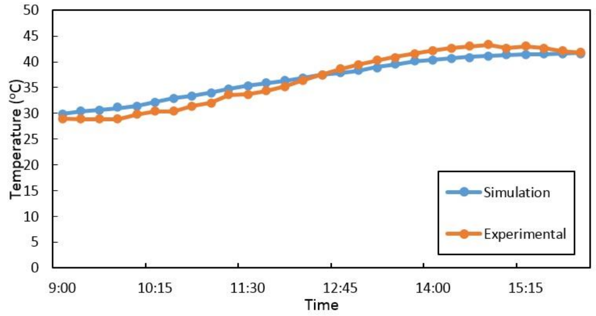

Figure 9. Sericite mica temperature at point 2 for simulated and experimental

Table 4 shows the percentage error between the simulated and actual data from the experiment. The percentage error for mica sericite temperature data between the experiments and simulation shows the highest value because of the assumptions that the material is solid whereas in the real condition it was a porous material with very low porosity value. However, with below 5% and 10% for average error and maximum percentage error respectively for all three parameters, it can be concluded that the developed CFD model can be used to represent the actual conditions of the field and can be used for subsequent analysis of the drying system.

Table 4. Percentage error between the simulated and actual data from the experiment

Parameter	Average error (%)	Maximum error (%)
Drying chamber temperature at point 1	2.0	6.3
Drying chamber air flow at point 1	0.6	1.9
Sericite mica temperature at point 2	3.5	6.5

B. Analysis for Different Temperature Interval

In this study, the CFD simulation was used to study the effects of different temperature interval. The boundary data for the drying chamber inlet is determined according to the field experiment. Two different intervals were studied ie 60-85°C (interval A) and 70-95°C (interval B). Table 5 shows the summary of the data from the no-load field experiment of the two intervals tested together with continuous ventilation for comparison.

Table 5. data from the no-load field experiment for the continuous, interval A and interval B.

	Continuous	Interval A	Interval B
Average drying chamber temperature without ventilation – blower "off" (°C)	-	53.6	52.3
Average time of without ventilation - blower "off" (min)	-	24.8	37.0
Average drying chamber temperature with ventilation - blower "on" (°C)	47.2	60.2	69.7
Average time of with ventilation - blower "on" (min)	-	11.3	9.1
Total ventilation time - blower "on" (min)	360	113.0	72.0
Average air flow in the drying chamber (per hour)	3.5	1.03	1.09

It is found that during the with ventilation period, the average air temperature increases when higher maximum temperature was set. When the blower turns on, interval B produce higher temperature in the drying chamber with the average temperature of 69.7°C. However, for the average temperature during the blower switch off ie without ventilation, it is found that interval A gives a higher temperature of 53.6°C. This happens because for interval B the period for blower "off" ie no ventilation is longer than interval A causes the temperature to decrease more before the blower is switch on again. The only component that consume electrical energy in the developed system was the blower. For continuous ventilation, the blower was continuously turn "on" for 360 minutes in 6 hours. From the data shown in Table 5, compared to continuous ventilation, the total energy consumption by the blower was reduced by 68.6% for ventilation with interval A and 81.9% for ventilation with interval B.

Figure 10 shows the temperature distribution of the sericite mica at the end of the drying period. Figure 10 shows that the temperature of sericite mica located near the inlet was higher compared to one that located further away for all conditions.

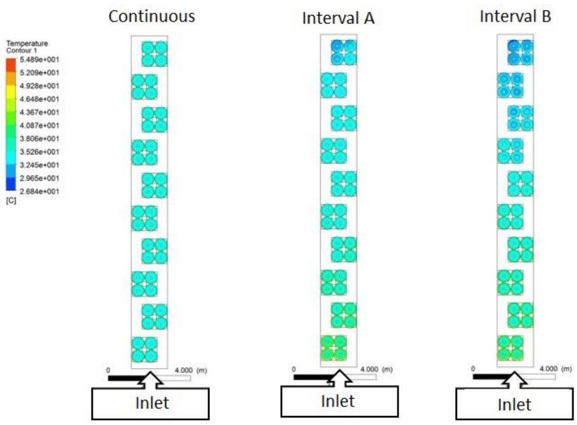

Figure 10. Sericite mica temperature distribution for interval A and B

Table 6 shows the results of sericite mica temperature at different pallet position at the end of the 6 hours CFD simulation period. Table 6 show that interval B produce higher temperature difference between sericite mica at different pallet which is 6.0^{o}C compared to interval A which is 5.4^{o}C.

Table 6. Temperature of the sericite mica at the end of the CFD simulation analysis for interval A and B

	palet 1 (°C)	palet 3 (°C)	palet 5 (°C)	palet 7 (°C)	palet 9 (°C)	Julat (°C)
Continuous	34.3	34.8	34.9	34.4	33.8	1.1
Interval A	38.0	36.3	35.2	33.9	32.6	5.4
Interval B	38.1	36.4	35.5	33.6	32.1	6.0

From the results of the CFD simulations for different temperature intervals, interval A was selected to be used compare to interval B. Interval A was selected because of two factors. The first factor was beside producing higher sericite mica temperature, the temperature difference between sericite mica at different pallets location was lower. It shows that the product is having a more uniform temperature distribution although it was located at different location in the drying chamber. While the second factor was interval A had a lower temperature setting for the blower to function whic is at 85^{o}C compared to interval B which is 95^{o}C allowing the blower to function with lower solar radiation intensity. This can maximize the blower function time to increase the flow of air in the drying chamber but at the same time it can saved up to 68.6% of the electricity consumption compared to the continuous ventilation method.

C. Analysis for Different Temperature Range

In addition to setting the minimum and maximum temperature values for the blowers to switch on and off, the range or span between minimum and maximum temperature also affects the duration of the blower functioning that affect the temperature in the drying chamber. The result of the different interval analysis found that interval A was able to produce optimum combination of temperature and electrical energy usage therefore interval A was used as a basis for different temperature range analysis. To study the effects of the different ranges, two intervals with different ranges were analysed which are range A with a temperature range of 25^{o}C and a new interval which is range A1 with a minimum and maximum temperature value of 70 to 85^{o}C that gives a temperature range of 15^{o}C. Table 7 shows the data from field experiment for both ranges. From table 7 it is found that range A1 produce higher average temperature during the blower on and lower temperature during blower "off" compare to range A. The total amount of time the blower "on" during the drying period was similar for both range

Table 7. data from the no-load field experiment for the two-temperature range tested

	Range A	Range A1
Average drying chamber temperature without ventilation - blower "off" (^{o}C)	53.6	59.9
Average time of without ventilation - blower "off" (min)	24.8	8.1
Average drying chamber temperature with ventilation - blower "on" (^{o}C)	60.2	52.7
Average time of with ventilation - blower "on" (min)	11.3	16.4
Total ventilation time - blower "on" (min)	113.0	114.0
Average air flow in the drying chamber (per hour)	1.03	1.09

Figure 11 shows temperature distribution of the sericite mica at the end of the drying period. Once again, for both range the temperature of sericite mica located near the inlet was higher compared to one that located further away. Table 8 shows the results of sericite mica temperature at the end of the 6 hours CFD simulation period at different pallet location. From table 8 it shows that the temperature difference for range A1 is higher at 7.1^{o}C compared to the range A which is only 5.4^{o}C

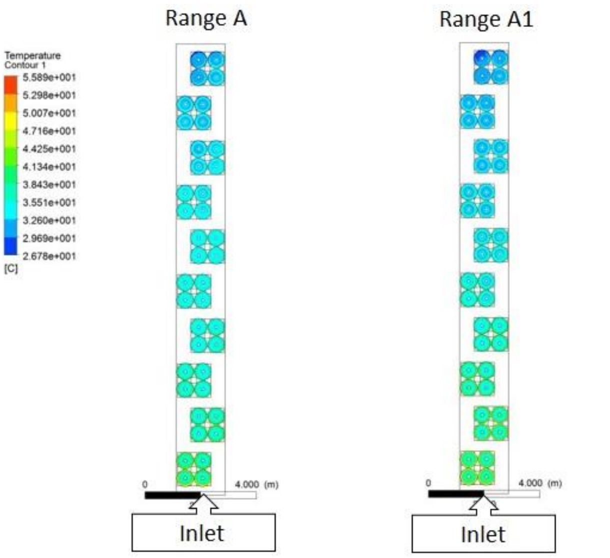

Figure 11. Sericite mica temperature distribution for range A and A1

Table 8. Temperature of the sericite mica at the end of the CFD simulation analysis for range A and A1.

	palet 1	palet 3	palet 5	palet 7	palet 9	Differences
Range A	38.0	36.3	35.2	33.9	32.6	5.4
Range A1	38.5	36.2	34.7	32.8	31.4	7.1

From this simulation results, range A with a temperature range of 25°C is better than range A1 with a temperature range of 15°C. This is because range A produces higher temperatures at all pallet location except the first pallets and produces a lower temperature difference between sericite mica at different pallet location. Furthermore, for range A1, the frequency of the blower switch "on" and "off" was higher compare to range A. This situation results in higher wear and tear rates for range A1 and contributes to higher maintenance cost.

IV. CONCLUSION

From the results of the study it was concluded that CFD simulation results was comparable with actual experimental data for intermittent ventilation drying process. Comparisons between simulated and experimental data of drying chamber temperature and air flow and sericite mica temperature shows that the average percentage error was less than 5%. The CFD simulation results able to shows that different temperature interval and temperature range will affect the temperature of the product and also the drying chamber climate during the drying process. From the CFD simulation results, it was concluded that temperature range between 60 to 85°C shows a balance between increment in the product temperature, temperature uniformity of the product at different pallet position and also the electrical energy savings aspect of the developed solar dryer system.

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