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ANALYSIS OF THE OPERATION AND PERFORMANCE OF A SOLAR COOLING SYSTEM

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ABSTRACT: In recent years, renewable sources of energy have been increasingly sought after to shift the consumption of energy from conventional sources to clean energy sources. A myriad of applications exist to exploit solar, wind, geothermal and any other means to provide the required process. Solar energy systems can either produce electricity or hot water. Solar cooling systems are being installed to provide space cooling or process cooling in locations where sufficient thermal energy is present to operate the vapour absorption chiller to replace vapour compression systems. Thus since sufficient solar energy was incident on the building of the Oenology and Viticulture Research Centre at Buskett, it was used to generate hot water to operate a solar cooling system to supply chilled water to control the temperature of fermenting wine. Prior to the installation, process cooling was provided through a vapour compression system. Initially a control system was designed to operate the solar cooling system. The system could not operate during high solar radiation scenarios and thus significant number of experimentats were carried out to improve the operation and performance of the solar cooling system.

Keywords: Solar Cooling, Flowrate, Solar Radiation

1 INTRODUCTION

Cumulatively, the global winemaking industry produced 268.7 million hectolitres of wine in 2009. When converted to reflect the greenhouse gas (GHG) emissions, it is assumed that two kilograms of CO_2 are released into the atmosphere for every 0.75 litre bottle, contributing to significant GHG emissions [1]. Moreover, the majority of wineries are located in advantageous geographic positions for renewable energy systems to be incorporated within the facilities [2].

From research conducted by Axisa and Ghirlando [3], analysis of the data concluded that the geographic position of the Buskett Research Centre for Oenology and Viticulture was optimal to design and install a renewable energy system. The area records high levels of solar radiation throughout the year, without any hindrance from surrounding buildings. To reduce and offset the consumption of electricity required to power a conventional vapour compression chiller, two systems were installed at the research centre. A 19kW photovoltaic system was installed as shown in Fig.1 below to supply electricity to the grid to power the conventional chiller. Moreover, a 19kW vapour absorption chiller was installed to supply chilled water to provide wine temperature control during hours with sufficient solar radiation. The solar cooling system only consumes electricity to power the circulating pumps, sensors and the control system.

Figure 1: The systems installed at the Buskett Research Centre for Viticulture and Oenology

1.1 Aim and Objectives

The aim of the MSc research on which this paper is based was to carry out an analysis of the data regarding the operation and performance of the solar cooling system installed at the Buskett Research Centre for Viticulture and Oenology.

The objectives of this dissertation included:

- To carry out an extensive literature review to determine the factors which have a direct impact on solar thermal driven systems.
- To analyse operational data obtained through extensive experimentation.
- To provide sufficient cooling during the fermentation process.
- To identify potential optimization possibilities.

2 LITERATURE REVIEW

To determine the effectiveness of the tests to be carried out, other studies were reviewed. Moreover, research studies were analysed based on the ammonia-water thermodynamic process since the chiller installed at the research centre operates with this working fluid pair.

2.1 Analysis of the Vapour Absorption Process

The working mechanism of a vapour absorption system is based on four main components: the generator, absorber, condenser and evaporator. Both heat energy input and output are found in the thermodynamic process. The vapour absorption process starts when the current supply of thermal energy Q_G is in the required temperature range to operate the chiller. Heat is transferred to the strong solution being pumped into the generator (4), shown in Fig.2, causing a separation of the refrigerant from the absorber due to the distinct boiling points of the working pair.

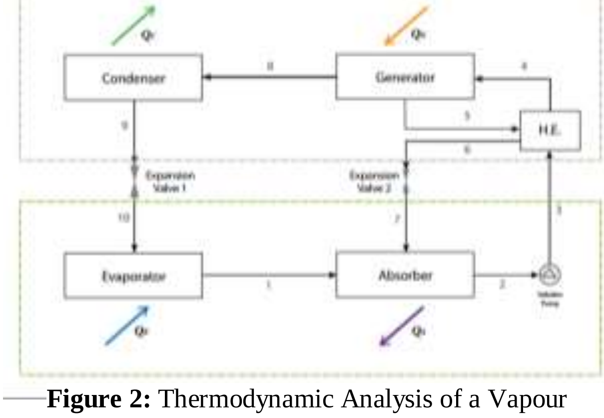

Figure 2: Thermodynamic Analysis of a Vapour Absorption Process

Two streams flow out of the generator. The absorbent (water) (5), flows first through the heat exchanger (6) and then through an expansion valve to reduce the pressure of the solution back to the lower pressure limit. The main purpose of the heat exchanger is to reduce the temperature of the solution flowing out of the generator towards the expansion valve. This transfer of heat is a method to increase the solution temperature from internal waste heat in the vapour absorption process. The resulting low-pressure solution (7) enters the absorber. The second stream (8) flowing from the generator to the condenser is made up of refrigerant, mainly high-pressure ammonia vapour, where it is condensed at the condensing temperature and pressure to result in high pressure ammonia liquid. In the condenser, heat in the form Q_C is expelled through the heat rejection system installed to result in a high pressure saturated solution (9). Another expansion valve lowers the pressure back to the lower pressure range (10) to match the pressure of the evaporator. In the evaporator, heat from the chilled water generation loop is transferred to the ammonia solution. Thus the low pressure liquid refrigerant vaporizes and flows to the absorber (1).

The solution from the generator absorbs the refrigerant vapour from the evaporator in the absorber resulting in a strong solution (2) where an amount of heat Q_A is rejected to the surroundings in the process. Since water and ammonia have a high affinity to each other, water found in the absorber has the ability to absorb ammonia in high quantities. The absorptive process reduces the absorber pressure, increasing the amount of vapour that is absorbed from the evaporator. The solution is then pumped by a solution pump from the absorber to the generator pressure and the process is repeated.

2.2 Applications of Solar Cooling Systems

Vapour absorption chillers are highly versatile and could be installed in locations where solar thermal energy or waste heat is sufficiently available to provide hot water in the required temperature range. Single stage vapour absorption chillers operate with low grade heat while medium-to-high grade heat is fundamental to operate multi-stage chillers. Moreover, using waste or renewable source of energy would curtail the consumption of electricity to supply either process or space cooling. Such systems could be integrated in a multitude of applications such as wineries, office spaces and storage facilities. To determine the factors which have a direct impact on the operation and performance of such systems, other case studies were analysed. In 1991, Mugnier [4] designed and installed a solar cooling system to provide space cooling in a wine cellar. Vacuum tube collectors were installed to provide the required thermal energy to operate a water lithium-bromide absorption chiller with a nominal cooling capacity of 52 kW to limit the use of the current centralized mechanical ventilation system. From system operation, data analysis showed that the chiller produced more than 2200 kWh of cooling capacity when adequate solar radiation was available (May to September). Although this system does not directly cool wine through heat exchangers, it maintains the surrounding air in an acceptable temperature range. Such a system is ideal as it provides the required cooling with minimal electricity input during the period when higher ambient temperatures would be recorded, possibly hindering the quality of the resulting wine [4]. It should also be highlighted that the system has been in operation for more than 15 years without any significant issues [5].

As part of the Solar Water Heating Innovation Grant Scheme in New Zealand, a technology and feasibility study was carried out by Kerr [6] for Sectus Winery in Blenheim. Such incentives are devoted to introducing more sustainability in a country famed for its wine. As in any winery, the main energy consumer is attributed to cooling of wine, where wine production at this facility is approximated to be one million litres. The location of the winery is ideal as the city records optimum sunshine hours each year. At the start of the study, cooling was provided through a 350kW vapour compression refrigeration system coupled with heat recovery from the refrigeration system itself assisted with 45 kW of electric resistance heating. Furthermore, out of 323 MWh of electricity consumed, it was estimated that 80% could be solely attributed to maintaining low temperatures during the fermentation processes.

A major restraint of the current system was that it was operated at night due to low electricity tariffs while a well-integrated solar cooling system could also provide cooling during daytime hours. Thus, Kerr considered the peak cooling output required coupled with thermal losses throughout the system; a 35kW solar cooling system with $72m^2$ of evacuated tube collectors was proposed. Simulations of the proposed system were carried out using TRNSYS. The cooling potential was estimated to reach 40 MWh equivalent to savings of $6000 each year and a payback period of 17.5 years. The annual solar fraction obtained from the solar collectors was estimated to be 46%. Solar fraction is calculated from the total energy obtained by solar energy divided by the total energy consumed by the system. Higher energy savings are calculated in proportion to higher cooling demand as the use of the auxiliary heater contributes to a lower proportion of the total energy input [6].

Another study was presented by Best et al. [7]. The Agro-Food Industry in Mexico presented a continuous increase in production, reflected in an increase in the cooling and freezing demand required by the manufacturing processes. In 2012, the electricity consumed for industrial refrigeration systems was 7.8% of the total power consumed in Mexico. Thus a cooling system that uses renewable energy would immediately affect the load on the Mexican electricity generation plants. The authors based their research study on a pork processing factory incorporating a modern production area where the pork cuts are packed and frozen. An added value plant is also found on-site where the cuts are individually frozen. The process requiring temperatures ranging from -2°C to 2°C was chosen for its vicinity to the operating ranges of current vapour absorption chillers. The study sought to model and optimize in TRNSYS the system chosen to operate at the factory. From the results, it was concluded that to limit initial costs and the size of the solar field, a nominal capacity of 515kW of cooling power was chosen. The solar fraction used throughout the year was deemed to be high as the system could operate continuously and provide sufficiently hot water for the chiller to operate. As a result, a solar cooling system in this factory was deemed to have potential as it could provide up to 758,400 kWh of chilled water per year, reduce cost of primary energy use and green-house gas emissions.

High solar fraction values improve the overall coefficient of performance of the system as the use of auxiliary heating methods is curtailed. A transient analysis research study was carried out for a solar cooling system based in Guayaquil, Ecuador. Naranjo-Mendoza et al [8] modelled a system using TRNSYS to partially satisfy the demand in an office building. The chosen city records optimal solar radiation values throughout the year together with an average ambient temperature of 27°C, meaning that a cooling load is constantly available. The model to be simulated was composed of a single effect lithium-bromide water vapour absorption chiller, evacuated tube collectors and a hot water storage tank. The collector aperture area, volume of the storage tank and mass flow rate through the solar collectors was optimized to achieve maximum solar fraction without unnecessary initial costs.

Economic feasibility for a certain location is as important as the radiance levels in the region. High capital costs related to solar cooling systems impede direct competition with mechanical compression chillers unless a government incentive is available to subsidise the project. It was highlighted that amongst various combinations, single-effect absorption chillers with heat supplied from evacuated tube collectors proved to be the most feasible across various locations. Multi-effect chillers were deemed not feasible for locations with low irradiance as these require high-grade thermal energy. The International Energy Agency forecasts a reduction of the overall total cost between 35% and 45% till 2030. The ever-increasing prices of fossil fuels positively affect such technologies [9].

An overview of a data collection exercise was carried out by the Quality Assurance in Solar Heating and Cooling Technology from various solar cooling systems across Europe. Results revealed that only flat plate collectors and evacuated tube collectors were commonly considered. Conventional cooling and heating methods have highly improved in energy efficiency, reducing further the competitiveness with the proposed renewable methods. Lack of awareness regarding the beneficial impact on the environment from reducing traditional energy consumption was prominent [10].

Infante Ferreira and Kim [11] published a study on how renewable technologies can be installed in the residential sector. Residential cooling accounted for 5900 PJ of energy consumption in 2011 across the globe. The authors noted that most installations were mechanical chillers coupled with a photovoltaic system since solar cooling systems are still not feasible for household applications.

3 SYSTEM DESCRIPTION

The system at Buskett has been designed to operate as a closed loop system with active solar thermal energy transfer from the solar collectors to the hot water storage tank. Three distinct closed loop hydraulic (water) circuits are present together with two secondary loops.

3.1 Hot Water Generation Circuit

The hot water generation loop is composed of two circuits. In the primary loop, the hot water supply is generated and sustained using evacuated tube heat pipe solar collectors, namely HRJ7-30/1.8 manufactured by Hi-MIN China. Seventeen solar collector arrays at a collector slope of 20˚ are installed in two sets on separate roofs with a total collector aperture area of 51m^2. One set comprises of twelve collector arrays in three rows of four solar collectors in series, each connected in parallel. The second set is composed of five solar collector arrays in series installed on the upper roof. A 245-litre tank is used to store hot water and supply the chiller and solar collector arrays during operation. In standby mode, since the variable flow circulating pump is switched off, water flows by gravity into the hot water storage tank, henceforward named the drainback tank. This minimizes any damage which could arise from stagnant water in the solar collector arrays.

3.2 Heat Rejection Circuit

Another variable flow circulating pump provides the necessary head to circulate water to a v-shaped Güntner 60kW dry re-cooling unit. The shape improves the rejection of heat to the surroundings. Heat is extracted when forced air flows over the fin of the circulating heat exchanger to result in lower temperature cooling water. The capacity required to provide the adequate heat rejection should be as a minimum double the chiller capacity. Whilst dry re-coolers are easier to install than wet re-cooling systems, this technology is limited by the ambient temperature. This limitation restrains the performance of the vapour absorption chiller during operation in the summer months due to the high temperatures recorded across the Maltese Islands.

3.3 Chilled Water Generation Circuit

Low pressure hot water from the drainback tank flows to a Pink Gmbh 19kW vapour absorption chiller using ammonia-water as the absorbent refrigerant working pair. Cold water produced by the chiller flows to a 2300-litre storage tank through a closed loop heat exchanger, installed on the ground floor. As a result of the tank's insulation, the chilled water temperature only increases by 1˚C every 24 hours, effectively storing chilled water for long periods of time. A constant flow circulating pump is used to circulate water from the tank back to the chiller at a pre-set flowrate.

3.4 Wine Storage Facilities

The research centre has been equipped with numerous storage facilities to store the grape juice. The first type are vats, built from stone to facilitate heat dissipation to the surroundings whilst chilled water is circulated through stainless steel heat exchangers. Moreover, two 2500L stainless steel tanks with jacket heat exchangers were incorporated, enabling the tanks to be connected to the chilled water supply. Finally, a number of 120L micro-vinification stainless steel tanks were installed to facilitate the fermentation process when small batches are to be stored.

During the fermentation process, an exothermic reaction occurs when glucose, fructose and yeast react and convert to carbon dioxide, ethanol and thermal energy.

3.5 Control System

A dynamic control load model for the solar cooling system was developed by Agius [12] based on two separate systems: a Model Predictive Control (MPC) methodology and a data monitoring and acquisition system. MPC was chosen amongst other algorithms as it offers higher flexibility during the design stage and reliability during operation. These can also handle and manipulate multiple control variables imposed by the solar cooling system with their respective constraints and physical limitations.

The data monitoring and acquisition (DAQ) system is fundamental to monitor the current operative state of the system. It connects the sensors to the control model to transfer data to the MPC model to execute the required control strategy in real-time. The DAQ system was designed and simulated in MATLAB and SIMULINK. The graphical user interface enables the user to examine the real-time measurements of temperature, pressure, and flowrate logged at a fixed time interval at the position of the sensors for each of the three distinct hydraulic circuits. Pyranometers were integrated into the system to measure the incident solar radiation at each time interval. The control system was essential to monitor the current operative state including the latest temperature and pressure readings to determine if the system is operating correctly [12].

4 RESULTS

The operational characteristics of the solar cooling system were obtained by exhaustively operating the system and analysing its response to the various climatic scenarios.

4.1 2016 Experimental Session

Two control strategies were identified as potentially suitable to be implemented during the harvest period. The first scenario was to continuously circulate chilled water through the micro-vinification tanks while the chiller was circulating chilled water through the chilled water storage tank. The second control strategy was to first reduce the temperature of the chilled water to the lowest possible reading the chiller could process. When the chiller switches to standby mode, the pump integrated in the secondary chilled water loop would be switched on to circulate chilled water to the micro-vinification tanks. The pump would operate throughout the night to absorb the thermal energy from the fermenting wine. Due to the significant difference in temperature between the two mediums, the temperature of fermenting wine could be adequately lowered.

During the following cycle, the circulation pump would be switched off and the process is repeated. This control strategy was deemed to be more suited to meet the demand imposed on the solar cooling system and was thus implemented throughout the harvest and fermentation period. For the solar cooling system to operate as necessary, certain repairs were carried out. The main issue was to upgrade the solar collector arrays to eliminate the leaks from the joints used to connect the individual arrays. As a result, air would leak into the system, causing the arrays to operate haphazardly in high solar radiation conditions. The system would then be switched off, suspending the supply of chilled water and thus the required wine temperature control, limiting the resulting quality of the wine.

4.1.1 Intermittent and Sufficient Solar Radiation

No auxiliary heating systems were integrated in the solar cooling system to support the generation of hot water during intermittent solar radiation. Therefore, the effect of fluctuating solar radiation on the overall operation was analysed. From the graph shown in Fig.3, it can be immediately noted that during periods of low insolation, adequate supply of hot water is only available to power the chiller after 12:00. Subsequently, as the temperature of the hot water from the solar collectors cannot be sustained, limited thermal energy is available impeding the chiller from operating further.

As the solar insolation starts to increase, the supply of hot water is renewed and the chiller is able to resume the production of chilled water. Radiation values fall below 200W/m^2, causing the chiller to operate intermittently for the next two hours. For the duration of the active state of the solar loop pump, it can also be highlighted that the temperature of hot water flowing from the solar collectors did not exceed 80^{o}C. In these circumstances, the low storage capacity of the drainback tank is advantageous as the volume can be heated to acceptable levels from limited solar radiation scenarios. This can also be a restraint as volume of hot water is only sufficient to sustain production for a short period of time.

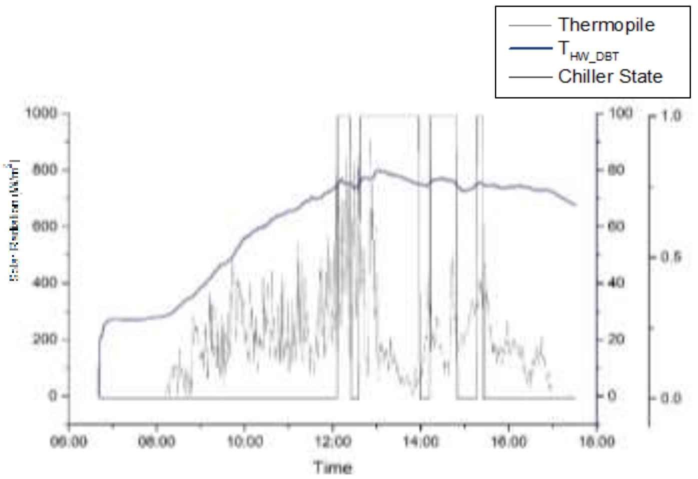

Figure 3: Operation Profile of the system during intermittent solar radiation

In comparison, the graph shown in Fig.4 depicts how the system operates in adequate solar radiation conditions. When the recorded values of solar radiation are high from the start of operation, the supply of hot water would be available earlier in the process. Contrarily to the previous scenario, the chiller switches on before 10:00 and switches off only when the solar radiation naturally decays after

16:30. Sufficiently high hot water temperatures were measured throughout the cycle, constantly supplying the drainback tank with the necessary thermal energy. These conditions are ideal when it is imperative that the volume of chilled water is at a low temperature to control the fermentation process.

The effect can also be noted on the cumulative energy consumed during the two scenarios. The total energy consumed by the re-cooler was less than 3kWh while the chiller consumed less than 0.5kWh. On the contrary, after constantly operating during sufficient solar radiation, the chiller consumed 4kWh while the re-cooler consumed 10.5kWh.

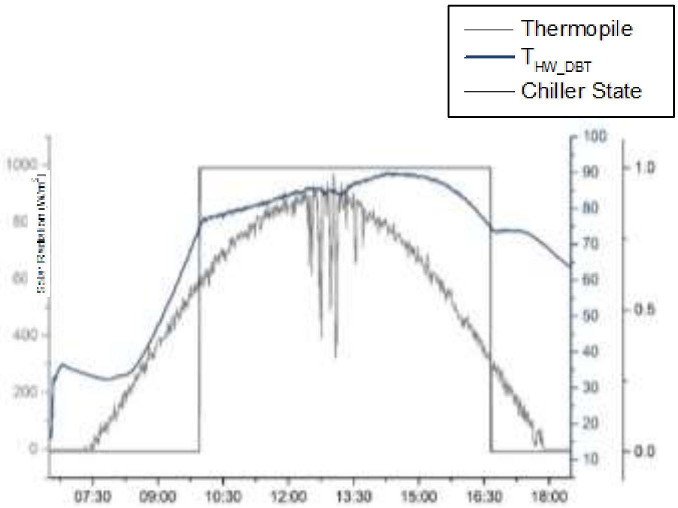

Figure 4: Operation Profile during adequate solar radiation

4.1.2 Temperature Profile of the Hot Water Generation Loop

Due to the position of the connections from the hydraulic circuits to the drainback tank, stratification occurs in said tank. As can be seen in the graph below, the temperature of hot water flowing out of the solar collectors ranges from 80-90ºC while that flowing to the chiller is measured between 65-75ºC.

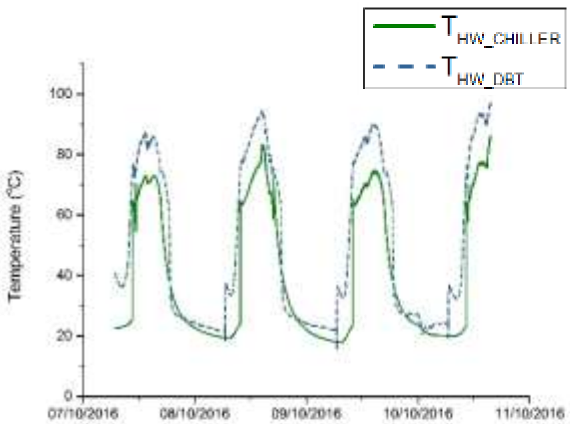

Figure 5: Temperature Profile in the primary loop of the Hot Water Generation Loop

4.1.3 Chilled Water Temperature Profile

A repetition in the profiles can be noted from which a conclusion can be drawn. While the solar cooling system operates under transient nature of solar radiation, the chiller is able to supply chilled water in a steady-state manner with a high degree of repeatability as shown in Fig.6.

The profile of the fermenting wine is super-imposed on the graph shown in Fig. 6 (T_{WINE}). When chilled water is first circulated through the vinification tanks, the temperature of the chilled water (T_{CWST}) is seen to increase at a rate faster than for subsequent operation cycles due to the higher initial wine temperature. The temperature of the wine is lowered from 23ºC to 18ºC in a few hours due to the increased capacity of the chilled water to absorb heat. It can be noted that heat absorption occurs at such low temperatures while as the chilled water temperature increases, the ability of the chilled water to absorb heat is limited due to the minimal temperature difference. After two cooling cycles, the initial wine temperature is seen to be lower, reducing the starting temperature from 23ºC to 19ºC. Prior to these experiments, the solar cooling system could not control the temperature of the wine, resulting in poor quality wine.

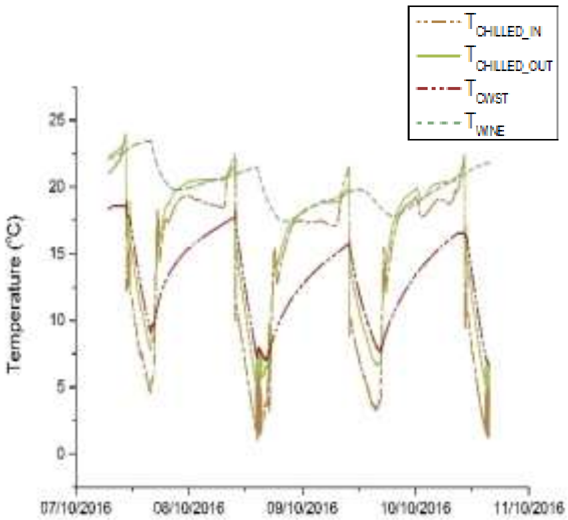

Figure 6: Temperature Profile of the Chilled Water including fermenting wine temperature profile

4.1.4 Temperature Profile of the Re-cooling Loop

Higher ambient temperatures impede the dry re-cooler to produce cooling water at temperatures lower than the surrounding ambient temperature. It can be highlighted that no significant temperature difference is observed during operation between the ambient temperature and the temperature of the cooling water flowing from the re-cooler to the chiller. Moreover, the difference between the incoming and outgoing flows has been adversely affected, reducing it from 7K to 5K, depicted by the temperature profile shown in Fig.7 below.

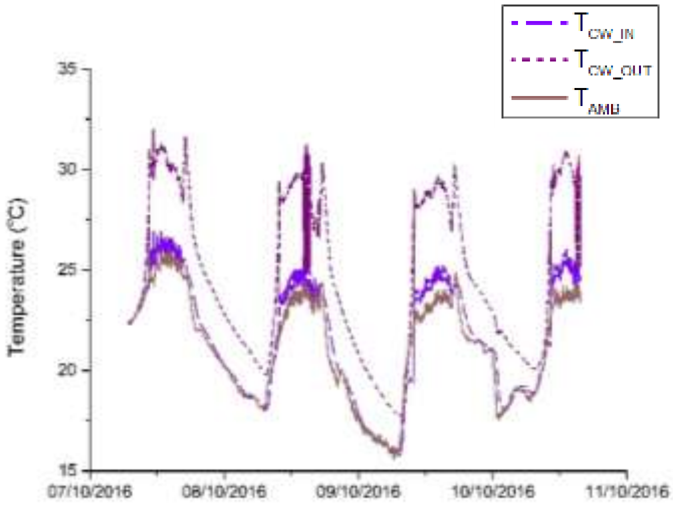

Figure 7: Re-cooling Loop Temperature Profile

4.1.5 Performance of the System

After a signal is issued for the chiller to start, the high temperature difference in the CWST leads to a relatively high COP. It then starts to decay when the load on the chiller is lower. As the chiller operates at a chilling capacity base load of 10kW, the performance is impaired when the temperature difference in the chilled water hydraulic circuit is minimal. Producing chilled water below 5°C causes the chiller to operate inconsistently. Immediate improvement in the operation of the vapour absorption chiller would be noted if a percentage of glycol solution would be added to the present fluid as it would impede the solution in the condenser from freezing. The intermittent hot water supply on 8th October is reflected in the graph shown in Fig.8.

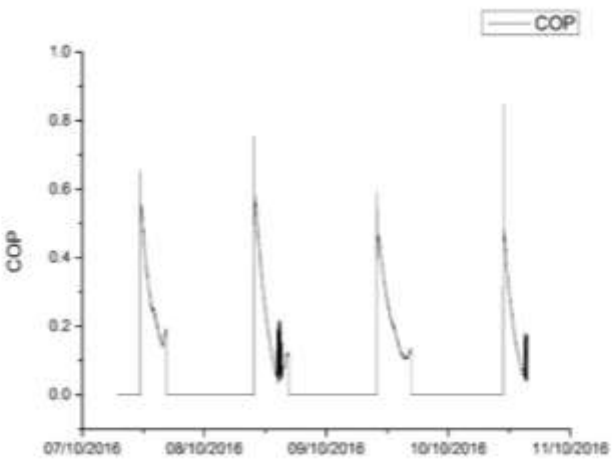

Figure 8: System Performance

4.2 2017 Experimental Session

The opportunity rose to carry out further tests on the solar cooling system. Since the tests during the previous harvesting period were constant flow analysis of the hydraulic circuits, a test procedure was designed to determine the effect of variable flow on the hydraulic circuits. From the technical specifications of the pumps and their respective position in the circuit, five flowrates were determined to be tested. The pumps which could be manually controlled were those installed in the primary and secondary loops of the hot water generation loop and in the re-cooling loop. It was imperative that when the chiller starts to supply chilled water, the temperature in the chilled water storage tank would be at a chosen value for the load to be constant. Moreover, the flowrate setting of the pumps not being tested were kept constant. Thus, the effect of the flowrate on the hydraulic circuit could be accurately determined.

Due to the lack of wine processed at the research centre during 2017, an experimental set-up was designed to heat the chilled water. Water from the chilled water storage tank would be circulated into a tank where a 6kW electric heater would heat the volume of water which would to be then cooled down in the following experimental session.

4.2.1 Variable Flow Analysis of the Hot Water Generation Primary Loop

The experimental flowrate was set when the control system switches on the pump at 06:30am. From the results it could be concluded that the higher the flowrate, the lower the temperature of the hot water generated in the evacuated tube collectors. A high flowrate is ideal during very high solar radiation conditions to control the temperature. On the contrary, a lower flowrate is advantageous to improve the operation period during mild or intermittent solar radiation scenarios as more thermal energy could be transferred to the chiller with an adequate supply of hot water. As can be seen from Fig.9 below, a low flowrate enabled the chiller to operate for a longer period as the required temperature was available earlier all throughout dusk.

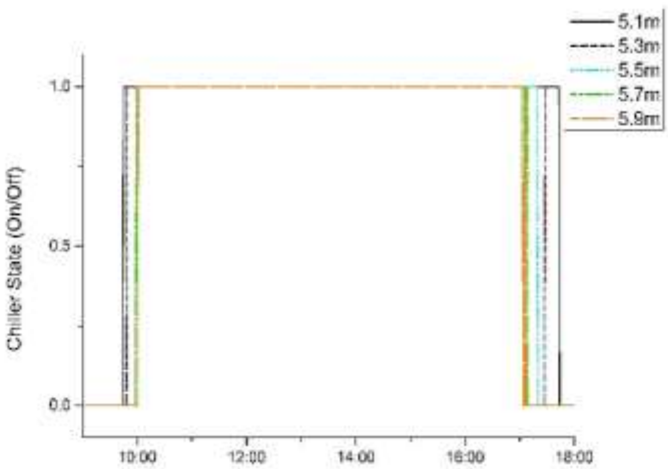

Figure 9: Length of Operation when analysing the primary loop

4.2.2 Variable Flow Analysis of the Hot Water Generation Secondary Loop

As can be concluded from the graph shown in Fig.10, it can be noted that the high flowrate circulating hot water between the drainback tank and vapour absorption chiller increased the heat losses, reducing the operating period. Therefore, in intermittent or decreasing solar radiation conditions, the flowrate should be lowered to conserve the thermal energy to improve the operating period.

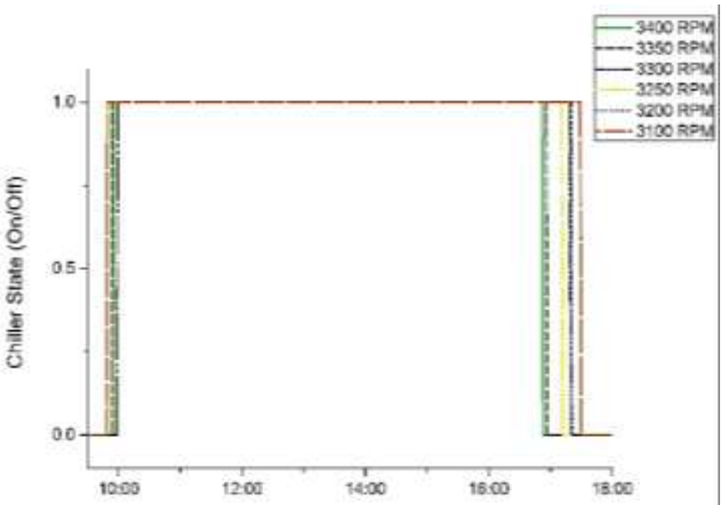

Figure 10: Length of Operation when analysing the secondary loop

4.2.3 Variable Flow Analysis of the Heat Rejection Loop

Reducing the volume of cooling water circulating through the dry re-cooler negatively affected the performance of the vapour absorption chiller. Since the required thermal energy was not being expelled, heat could not be absorbed from the chilled water generated loop. Thus, it was noted that the flowrate would not be reduced in the improved control strategy.

5 CONCLUSION

More than 700 hours were dedicated to experiment on the solar cooling system and determine the cause and effect of multiple variables. Initially, the system could not operate during high solar radiation conditions due to the high thermal energy yield from the solar collector arrays. Leaks from the solar collector arrays resulted in the probability of steam being generated and the system had to be switched off prematurely to prevent any damage from occurring to the system.

From the thorough testing, it could be concluded that due to the low volume storage of hot water, sudden cloud cover could limit the output temperature of hot water from the solar collector arrays and thus the system goes to standby mode until sufficient solar radiation is available. During the design stage, the solar cooling system was designed to shift a percentage of the process cooling from the vapour compression system to the vapour absorption system. The former required some repairs, resulting in the load to be solely met by the solar cooling system. Two control strategies were tested and it was decided that chilled water would be circulated to the micro-vinification tanks after the temperature in the CWST was suitably low.

From the test runs carried out during 2017, tests were carried out to determine if a row of solar collector arrays could be eliminated without impeding the sufficient generation of hot water. After four solar collector arrays were eliminated, the hot water generation loop operated more harmoniously, removing the need to switch off the system during high solar radiation conditions. Variable flowrate analysis and control enabled the system to operate autonomously. This was a huge improvement when compared to the initial scenario where the system had to be continuously monitored.

Moreover, the length of operation improved by more than 50 minutes when the updated control strategy was tested. This enabled the fermenting wine to be controlled more precisely as the chilled water supply would be available throughout the night.

A number of recommendations were drawn from the exhaustive testing. The control system should be upgraded to include automatic flowrate control. Multiple temperature sensors should be included to monitor the system more accurately. Moreover, the power meters and control panel of the chiller could not be remotely accessed.

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