Innovative Stand-Alone Renewable Thermal Energy System for Viscosity Reduction of Heavy Crude Oil

M. Al-Mahmoodi*, A. Al-Janabi[1]*, S. Al-Obaidani*and N. Al-Rawahi*

* Sultan Qaboos University, College of Engineering, Department of Mechanical & Industrial Engineering

*Corresponding author: **ab.aljanabi@squ.edu.om**

Abstract:

Crude oil is a vital component of the global economy, with diverse applications in various sectors. Nowadays, most of the petroleum reserves correspond to heavy and extra-heavy crude oils that have high viscosity and low API gravity. Viscosity strongly influences the flow of heavy crude oil during pipeline transportation in terms of increasing the pressure drop and consequently increasing the pumping power. Overcoming these challenges is crucial for the cost-effective transportation of heavy crude oil while minimizing capital and operational expenses. This study is devoted to developing an eco-friendly sustainable thermal heating system to minimize the viscosity of heavy crude oils by implementing a novel and creative technique involving integrating solar energy with a phase change material (PCM). A heating station prototype was designed to maintain the crude oil within the

viscosity operating limit to less than 100cP (API gravity greater than 20◦API). The presented data showed that during the period 8:49:46 AM to 2:34:46 PM, the solar energy was enough to increase oil temperature to 63.21°C or higher, where the viscosity fallen below the critical threshold of 100 cP, signifying the transition to light crude oil characteristics. To achieve system sustainability, the PCM was used during the time span from 5:49:46 PM to 5:49:46 AM. The stored energy in the PCM during daylight was used to maintain the water temperature within the level required to enhance the oil viscosity. However, a challenge emerged during the time spans 5:50-8:48 AM and 2:40-5:50 PM, during which the gained heat by water was not sufficient to increase crude oil temperature to its minimum level of 63°C. To comply with this challenge, 7 Photovoltaic panels of size 330 W/m^2 were integrated into the system, to be utilized during the period marked by the encounter with crude oil possessing a viscosity exceeding 100 cP.

Keywords: Heavy Crude Oil; Heating Stations, Solar Energy; Phase Change Material; Sustainable Technologies

1. Introduction [1]

Crude oil is an effective element in the global economy. It plays a particularly significant role in its multiple uses in many economic sectors such as the industrial, logistical, and electrical sectors. The industrial sector relies on crude oil for its high uses in many applications (Nadirah et al., 2014).

[1] Part of this paper has been presented at the 1st GCC Engineering Symposium, Kuwait University in November 29th -31st in Kuwait.

The increasing demand for fossil fuels has become noticeable in recent decades, due to the massive economic development and rapid population growth which led to a gradual decrease in the reserves of conventional oil, including light and medium crude oil, which become rare and insufficient to meet the growing and accelerating rapid demand for energy. Therefore, to avoid massive scarcity, unconventional oil reserves have been considered the primary alternative to fossil fuels including heavy oil, extra heavy oil, oil shale, oil sands, tar sands, and tar (Ibrahim et al., 2019). However, it cannot be recovered and then transported in its natural state by the usual methods of production and transportation, as it requires added demand to ensure the ease of the acceptable flow rate compared to conventional oil, which is distinguished by its low production costs.

Viscosity is an important physical property besides density and boiling point ranges. It is considered a crucial factor that strongly affects its upstream recovery, midstream surface transportation, and downstream refining processes. It enormously impacts the fluidity of heavy crude oil as it plays an influential and significant role in transporting heavy crude oil through pipelines compared to other physical properties. Economic methods for recovering, transporting, and refining heavy crude oil is particularly important and related to capital and/or operating costs. Nowadays, most of the petroleum reserves in the world correspond to heavy and extra-heavy crude oils. Such crude oils have high viscosity and low API gravity, which complicate their production, transportation, and refining. Figure 1 shows the classification of crude oils by °API gravity and viscosity, (extra-heavy crude oil: viscosity greater than 10,000 cP and API gravity less than 10◦API, heavy crude oil: 100– 10,000 cP and 10–20 ◦API, light crude oil: viscosity less than 100 cP and API gravity greater than 20◦API) as per (Speight, 2015) and (Speight, 2014).

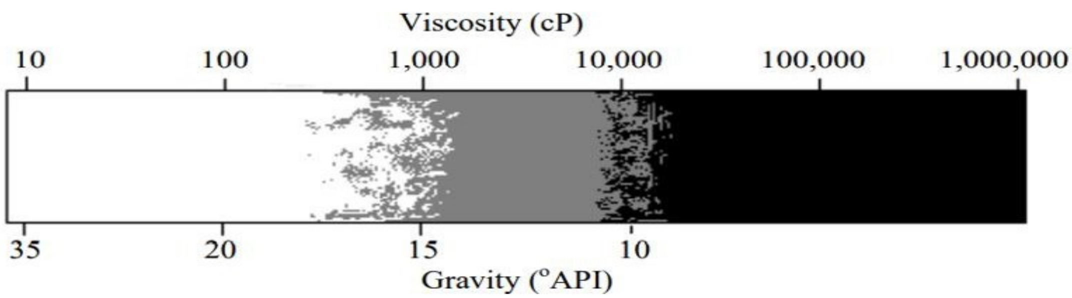

Fig. 1: Classification of crude oils by °API gravity and viscosity, (Falah, 2017)

Predictably, heavy, and very heavy oils will become an exceptional alternative to conventional oil in the future, but because of their composition complexity, their flow in normal cases is difficult to predict easily, which may cause severe problems. It has an influential and significant role in transporting heavy crude oil through pipelines compared to other physical properties and because of that, the friction between the oil's particles and the internal walls surfaces takes place causing a steep decline for the transported oil in a specified time. This issue is a serious obstacle in the fluidity and transporting process as it causes the pressure drop in the pipelines due to the frictional force and the internal surface walls of the pipelines (Taborda et al., 2017a, 2017b; Montes et al., 2019; Antoet al., 2020). Moreover, heavy oil coagulates completely when the temperature is lower than the pour point causing serious problems during transportation, especially in a cold offshore situation where there are deposits of wax and asphalt on the inner surfaces of the pipes causing a reduction in the effective flowing diameter causing clogging eventually leading to a huge pressure drop on the pipeline

(Martínez-Palou et al., 2011; Kumar and Mahto, 2017). This research study aims to clarify the various thermal heating techniques available for transporting heavy crude oil and highlights their pros and cons with the target that the acquiring would aid in creating an innovative practical solution through using a renewable thermal approach technique combined with phase change material to improve and enhance the transportation of heavy oils through the pipelines economically and environmentally. By combining solar energy and phase change material, this research study creates a contribution to the advancement of eco- friendly solutions for the transportation of heavy crude oils. The development of an efficient thermal heating system and the insights gained from investigations and economic evaluations would pave the way for more sustainable and environmentally friendly practices in the energy and transportation sectors.

2. Research Gap and Methodology

Presently, there is a significant lack of studies on heating approach methods as there are few reports in the literature reviews of studies dealing with the transportation of heavy crude oil using this technique. This challenge needs citation analysis and systematic review to develop a new technique for mitigating the high viscosity of heavy crude oils. Furthermore, to tackle the economic and environmental issues related to the thermal heating approach a renewable energy concept combined with phase change material is proposed to be implemented in this study. The methodology for addressing the research gap involves three consequence stages represented by Stage I) a comprehensive literature review to understand the working principles of the previous thermal heating system and address the main challenges associated with those techniques, Stage II) was devoted to designing a sustainable thermal heating system integrating solar energy and phase change material, and Stage III) the new system was subjected to investigation to study its thermal performance. A theoretical study utilizing mathematical modeling and advanced simulations was conducted. This analysis focused on predicting the solar thermal heating system's performance under varying conditions and served as a critical foundation for subsequent investigations, ensuring an informed research approach.

3. System Setup and Working Procedure

In this research, product design ideas were generated by considering technical specifications, design limitations, and engineering constraints. Technical specifications ensured the efficiency, safety, and sustainability of the system's design. These specifications included considerations for maximizing heat transfer rates, achieving high energy efficiency, and ensuring compatibility and integration among system components. Additionally, the system design addressed factors such as thermal storage capacity, system control and automation, safety, durability, maintenance, environmental impact, and costeffectiveness. The design analysis process explored three critical elements: design concepts, Main components of design concepts, and the working principle of design concepts. The approach involved developing a single design concept through functional decomposition, idea generation, selection criteria, feasibility analysis, and final system concept selection. To optimize the design of a solar thermal heating system, a systematic approach was employed to categorize its components into five main groups as illustrated in Figure 2.

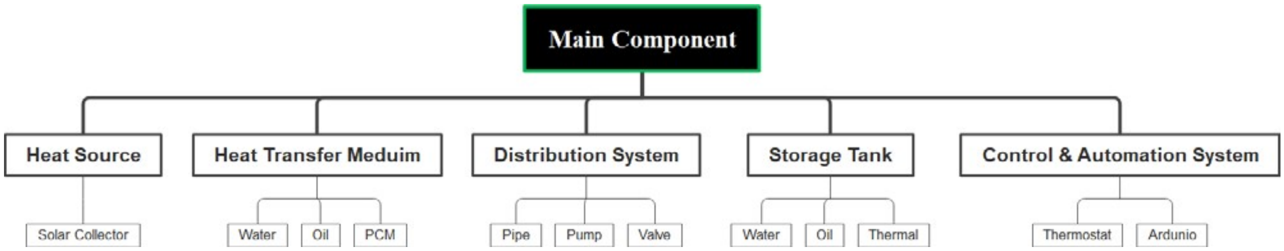

Fig. 2: The primary components of the system

The designed eco-friendly thermal heating system consists of three main components as shown in Figure 3; a single glass Flat Plate Solar Collector (FPSC), Oil heating station, Thermal energy storage (TES) solar collector. As sunlight impinges upon this surface, the consequential thermal energy is adeptly transmitted to a circulating aqueous medium (water) within a conduit network integrated within the collector's structure. Subsequently, the heated water is judiciously directed into an insulated reservoir housing heavy crude oil (heating station), where it fulfills the crucial role of tempering the oil to maintain a prescribed temperature range. The reservoir is equipped with temperature sensors and control mechanisms to maintain precision in temperature control. Within the oil storage tank, a sophisticated heat exchange system is integrated. A pump mechanism orchestrates the autonomous circulation of the heated water from the reservoir, through the collector, and back into the reservoir, ensuring the perpetuity of the heat transfer process. Concurrently, the system incorporates a distinct solar collector enveloped by a singular glass cover, featuring an internal chamber infused with a phase change material (PCM). This specialized collector seizes solar radiation and harnesses its energy to facilitate the heating of crude oil during instances of solar absence.

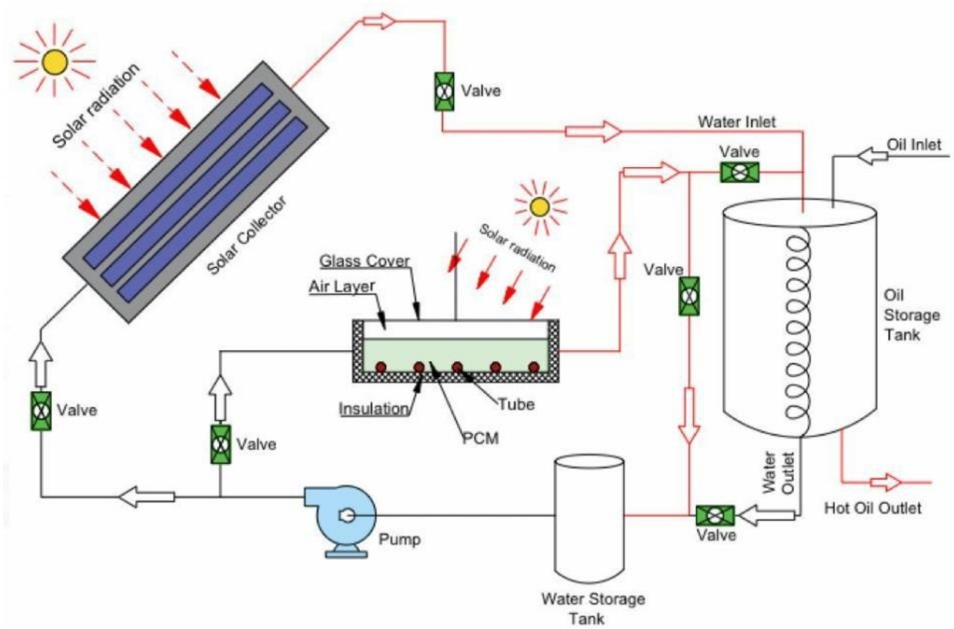

Fig. 3: Schematic diagram of the design concept

In this solar thermal heating system, a specific Phase Change Material (PCM) known as RT64HC PCM, with a melting point precisely at 64°C, had been carefully selected based on the system's requirements and design considerations. This PCM played a pivotal role by effectively storing and releasing thermal energy. When exposed to sunlight, the RT64HC PCM absorbed energy, transitioning from a solid to a liquid state, and securely stored this energy until it was needed for heating purposes. In the absence of sunlight, it gradually released the stored thermal energy, contributing to the continuous and controlled heating of heavy crude oil. Moreover, the PCM's unique property of reducing oil viscosity enhanced its flow characteristics, optimizing the efficiency and reliability of the entire heating process, making it a valuable technology for a range of industrial and energy applications. The given data, as shown in Table 1, provide valuable information about the properties and characteristics of the RT64HC PCM, enabling a comprehensive analysis of its behavior and performance. Iterative heat transfer exchanges orchestrated amongst the heated water, the PCM, and the oil play a pivotal role in the substantial reduction of the oil's viscosity, enhancing its flow characteristics.

Table 1: Thermo-physical properties of the RT64HC PCM

Property	Value	Unit
Latent heat of fusion (h_{fg})	250	kJ/kg
Specific heat capacity (c_p)	2000	J/kg. °C
Melting point (T)	64	°C
Density solid @ 20°C (ρ)	880	kg/m³
Density solid temperature (T)	20	°C

4. Results Analysis and Discussion

These descriptions delve into thermal behavior, focusing on solar energy measurement, data analysis in conjunction with solar energy availability, and the typical utilization of solar energy. They provide insights into the systems' dynamic responses over time. Figure 4 depicts the typical solar energy incident (Q) in Oman for October, showcasing it on a two-dimensional graph with a Y-axis and an X-axis. The Y-axis represents solar energy incident (Q), spanning from 0 to 900 watts per square meter (W/m²), while the X-axis indicates the time in hours, starting at 12:04:46 AM and concluding at 11:59:46 PM. The graph reveals distinctive phases: From 12:04:46 AM to 5:44:46 AM, there's no significant heat gain by the solar collector because it's typically nighttime, and the absence of sunlight during this time means there would be little to no heat gain by a solar collector. From 5:49:46 AM onward, there was a gradual increase in solar energy incidents, peaking slightly above 800 W/m², and reaching almost 830 W/m² at 11:59:46 AM. During this time, the solar collector received a significant amount of sunlight, making it an optimal period for capturing solar energy for water heating purposes. Following the peak around 11:59:46 AM, there was a gradual decline in solar energy incidents due to the natural movement of the sun across the sky. As the sun descended from its zenith, the angle at which sunlight reached the solar collector changed, resulting in a decrease in the intensity of sunlight. This decline continued until 5:54:46 PM when the solar energy incident reached zero, signifying the cessation of solar heat gain for the day. This decrease in solar energy was a result of the sun setting below the horizon, leading to the absence of direct sunlight.

Figure 5 presents a comprehensive depiction of the Flat Plate Solar Collector's performance. The Y-axis represents heat gained by the water (Q), ranging from 0 to 4000 watts (W). Simultaneously, the X-axis denotes time in hours, spanning from 12:04:46 AM to 11:59:46 PM. Initially, from 12:04:46 AM to 5:44:46 AM, no heat gain was evident, marking a period of inactivity due to the absence of sunlight during the nighttime hours. Commencing at 5:49:46 AM, a gradual ascent in heat gain became apparent.

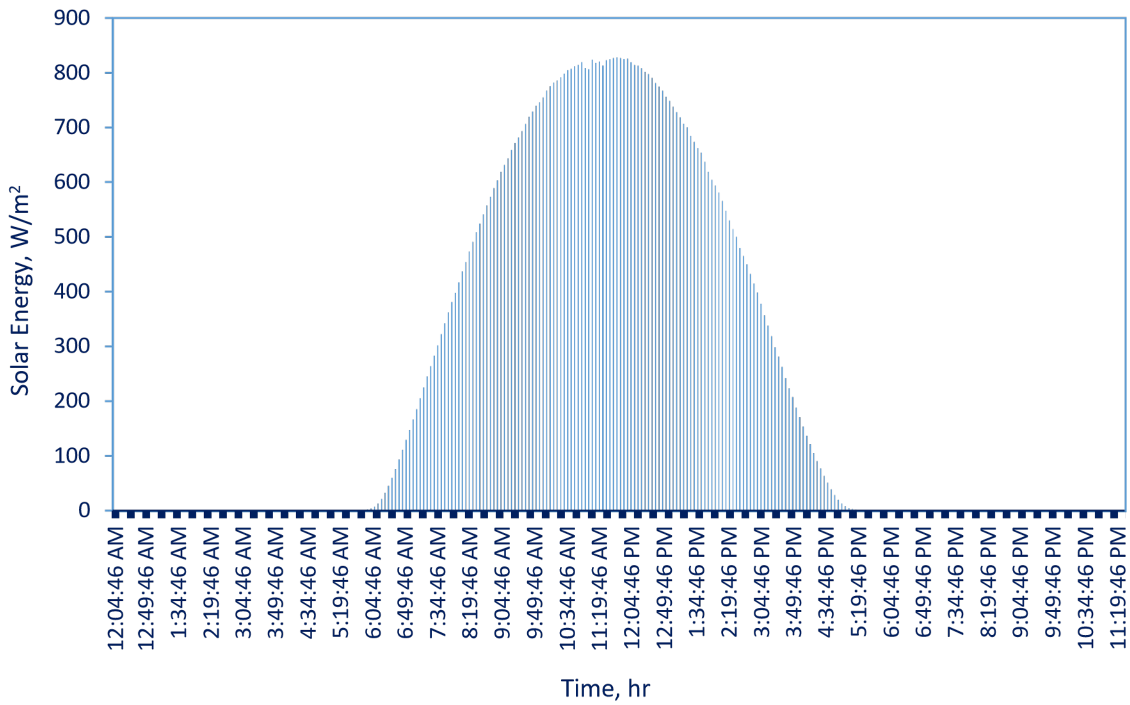

Fig. 4: Solar energy incident versus time

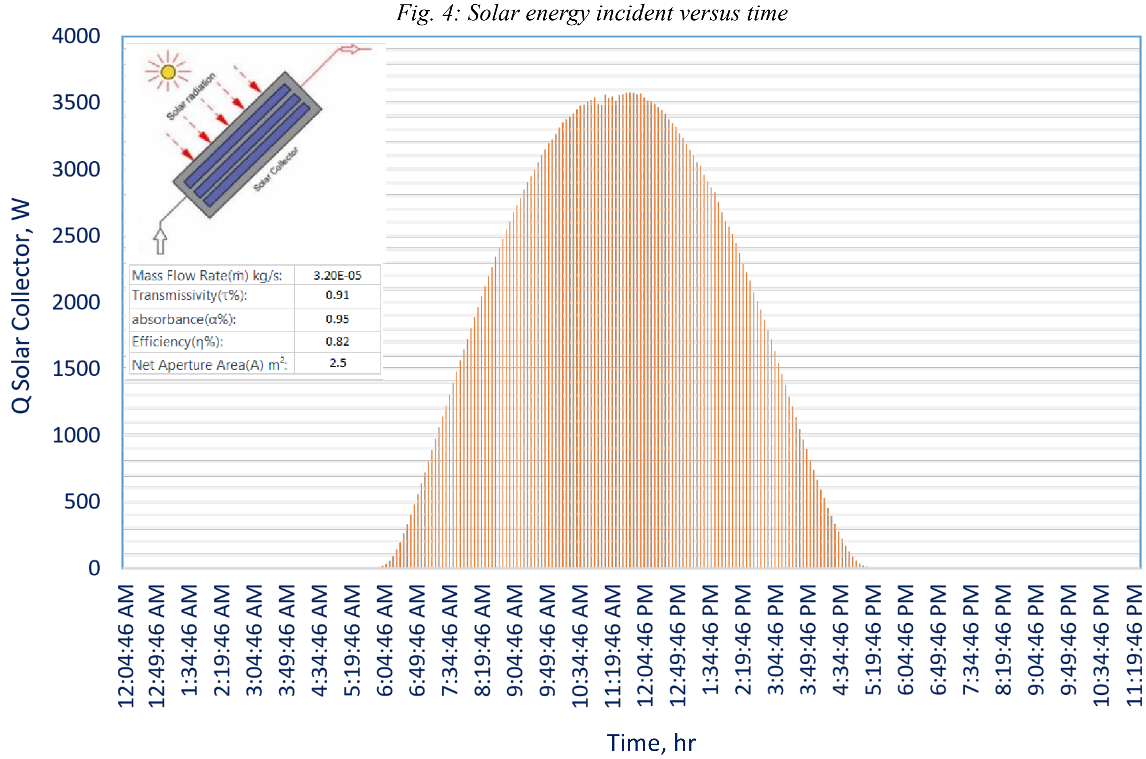

Fig. 5: Energy gain by the solar collector

This increase occurred as the sun rose and its angle in the sky allowed for more direct sunlight to be absorbed by the solar collector. This culminated at approximately 3578 W around 11:59:46 AM, signifying the peak heat gain of the day (taking into account the technical specifications of the thermal solar collector in terms of transmittance ($\tau = 0.91$), and absorbance ($\alpha = 0.95$)). Subsequently, heat gain experienced a gradual decline. This decline was a result of the sun's position shifting in the sky as it moved toward sunset. The changing angle of sunlight reduced the intensity of solar energy reaching the collector. Ultimately, the heat gain reached zero precisely at 5:54:46 PM as the sun set below the horizon, leading to the cessation of solar heat gain for the day. Following this point, heat gain remains at zero during the nighttime hours due to the absence of sunlight, and no further heat gain occurs until the next day when the sun rises again.

The temperature profile of water passing through the Flat Plate Solar Collector and the crude oil tank is presented in Figure 6. In both systems, the initial period from 12:04:46 AM to 5:44:46 AM signifies thermal stability, during which no significant temperature changes occurred. This stability was attributed to a lack of external heat sources affecting the systems during this time. Starting at 5:49:46 AM, a noteworthy shift occurred as the water in the FPSC and the oil in the tank gradually began to gain heat. This increase in temperature was directly attributed to the absorption of solar energy,

primarily represented by $\tau\alpha$, which signifies the transmittance (τ) and absorbance (α) of the collector. In the FPSC, solar radiation was absorbed, leading to an increase in the water temperature. Simultaneously, heat gain in the oil tank was facilitated by a heat exchanger, with heat transferred from the hot water. These heat absorption processes continued steadily until they reached their respective peak temperatures, approaching 26.75°C for the water and 27.85°C for the oil.

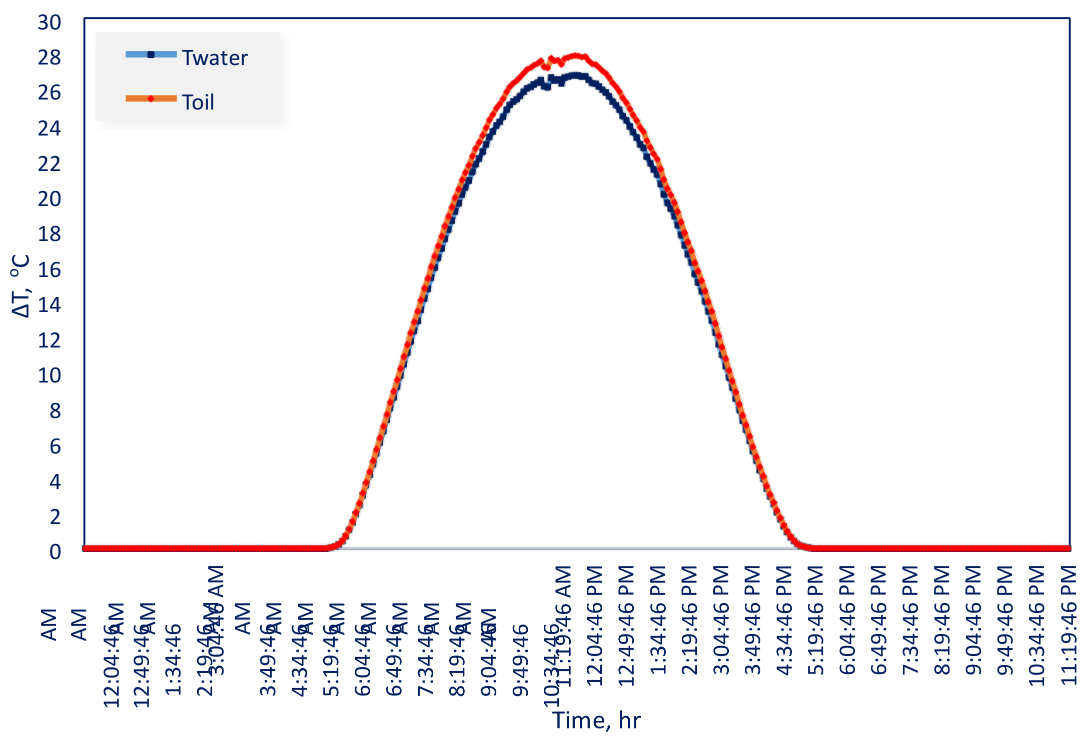

Fig. 6: Temperature profile of water and oil in the system

These peak temperatures were achieved at 11:59:46 AM for both FPSC and oil. Following the peak, there was a sharp and pronounced decline in the temperature leading to a return to zero at approximately 5:54:46 PM. This sharp decline signifies the cessation of solar energy absorption and heat transfer processes. As the sun's intensity diminishes, and heat exchange subsides, the temperature decreases rapidly, eventually reaching equilibrium with the surroundings. After returning to zero, both systems stabilize at a consistent temperature level, which is maintained until the end of the depicted time frame. This stable temperature reflects the balance between heat gained during sunlight exposure and heat dissipated to the environment, signifying a state of thermal equilibrium.

The correlation between crude oil viscosity in centipoises (cP) and oil temperature in degrees Celsius (°C) is presented in Figure 7. Notably, as the temperature of heavy crude oil gradually increased, there was a simultaneous decrease in the viscosity. The outlet temperature of the oil was progressively raised from 45°C to 72.84°C. Consequently, the oil's viscosity was exhibited a gradual decline, transitioning from 443.99 cP to 46.67 cP. This decline in viscosity was attributed to the increase in oil temperature, facilitated by heat transfer from the hot water to the crude oil. It's worth noting that crude oil with a viscosity of less than 100 cP is classified as light crude oil. Examining the graph, it becomes evident that at temperatures of 63.21°C or higher, the viscosity falls below the critical threshold of 100 cP, signifying the transition to light crude oil characteristics.

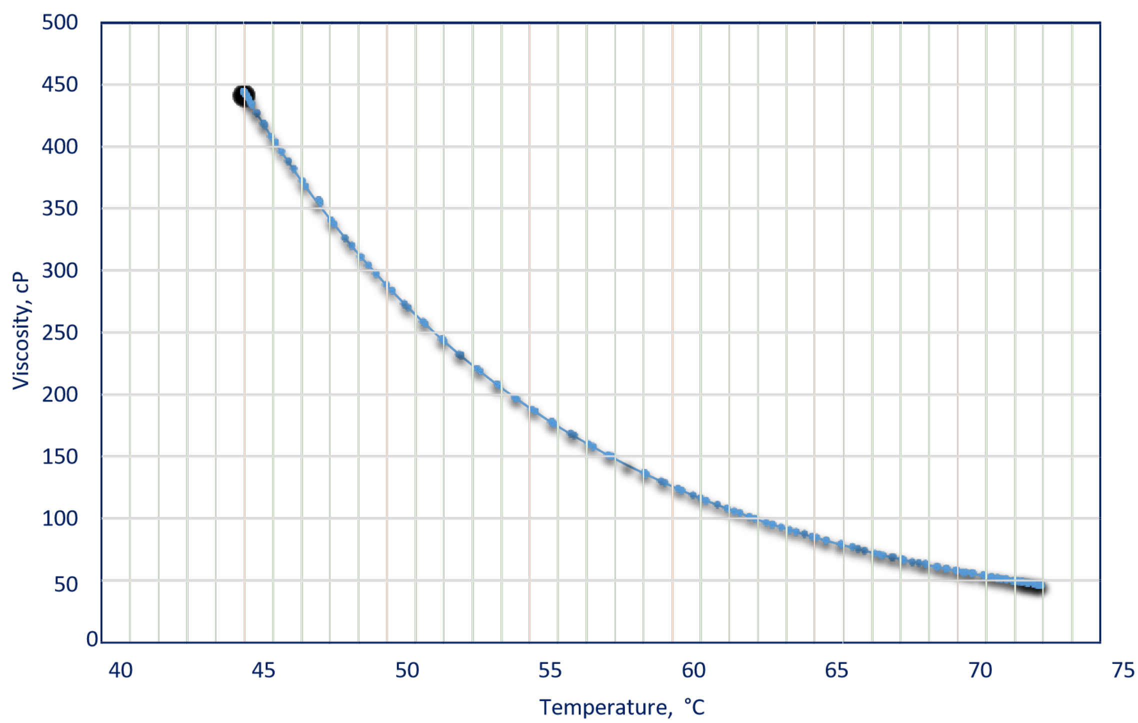

Fig. 7: Oil viscosity versus (μ) as a function of crude oil outlet temperature

Figure 8 provides a comprehensive insight into the dynamic interplay between the temperature and the viscosity within the context of heavy crude oil. Within the timeframe spanning from 8:49:46 AM to 2:34:46 PM, the system effectively achieved the objective of reducing the heavy crude oil's viscosity to the level characteristic of light crude oil. This transition was marked by the attainment of an oil temperature of 72.57 °C at 11:09:46 AM, corresponding to a viscosity of 47.66 centipoises (cP), thereby meeting the criteria for light crude oil classification. However, during the time spans 5:50-8:48 AM and post-2:40 PM till 5:50 PM a distinct challenge associated with achieving sustainability was observed. During this time span, the system encountered a temporal inefficiency in utilizing the solar collector. In other words, the gained heat by the water was not sufficient to increase the crude oil temperature to its minimum level of 63^{o}C where the viscosity starts to decrease to be below 100 cP. This challenge was handled by prompting the integration of a Photovoltaic (PV) panel into the system, to be utilized during the period marked by the encounter with crude oil possessing a viscosity exceeding 100 cP. To maintain the desired level of oil viscosity during this timeframe, 7 PV panels of size 330 W/m^2 were required. This strategic integration enabled the system to continuously mitigate viscosity, thereby preserving its operational effectiveness.

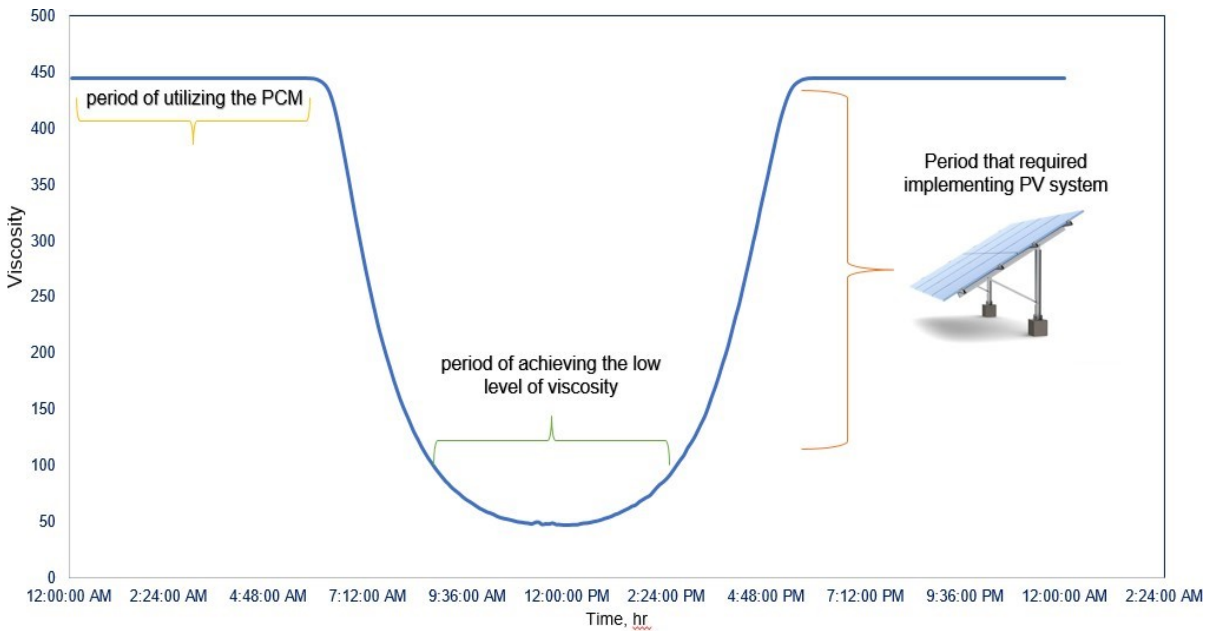

Fig. 8: Crude oil viscosity versus time

5. Conclusions

The presented data and analysis offer profound insights into the thermal behavior of the eco-friendly sustainable thermal heating system to minimize the viscosity of heavy crude oils. The numerical values, meticulously derived, underscore the profound significance of the findings at hand. The data revealed that solar energy incidents reach a zenith, peaking at nearly 830 W/m², signifying optimal periods for efficient energy capture during the zenith of daylight, particularly propitious for applications such as water heating. The heat absorbed by the flat plate solar collector exhibited an exceptional peak at approximately 12 noon with an amount of 3578 W where water approached its maximum temperature of 26.75°C. the heat absorbed by water in the solar collector was transferred to the crude oil to increase its temperature to the level where the viscosity becomes within the range of light crude oil. The designed system performed an increase in oil temperature by 27.85°C at the peak period. This was enough to reduce crude oil viscosity to fall below the critical threshold of 100 cP in the period of 8:49:46 AM to 2:34:46 PM, signifying the transition to light crude oil characteristics. To achieve system sustainability, the Phase Change Material (PCM) was used during the time span from 5:49:46 PM to 5:49:46 AM, totaling 12 hours. The stored energy in the PCM during daylight was used to maintain the water temperature within the level required to enhance the oil viscosity. The exceptional qualities of the PCM in terms of high melting point and a substantial latent heat of fusion render it an ideal choice for applications requiring energy storage at elevated temperatures.

However, a distinct operational challenge emerged during the time spans 5:50-8:48 AM and post- 2:40 PM till 5:50 PM, during which the system encountered a temporal inefficiency in utilizing the solar collector where the gained heat by the water was not sufficient to increase the crude oil temperature to its minimum level of 63^{o}C where the viscosity starts to decrease to be below 100 cP. This obstacle prompted the integration of a Photovoltaic (PV) panel into the system, to be utilized during the period marked by the encounter with crude oil possessing a viscosity exceeding 100 cP. To maintain the desired level of oil viscosity during this timeframe, 7 PV panels of size 330 W/m^2 were required. This strategic integration enabled the system to continuously mitigate viscosity, thereby preserving its operational effectiveness. In sum, these meticulously gathered numerical values underscore not only the theoretical implications of this research but, more importantly, the profound practicality that emerges from it. These findings emphasize the exceptional efficiency and remarkable adaptability of solar energy systems as eco-friendly systems to maintain the crude oil viscosity within the required working limit.

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