Tikrit Journal of Engineering Sciences (2025); 32(2): 1941
DOI: http://doi.org/10.25130/tjes.32.2.18

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Effect of Phase Change Material Heated by Solar Energy on the Flow Assurance of Heavy Crude Oil

Ghassan Al-Doori *[a], *Osama H. Al Naamani* [b], *Girma T. Chala* [b]
a Al-Imam University College. Tikrit, Iraq.
b International College of Engineering and Management, P.O. Box 2511, C.P.O Seeb, P.C. 111, Muscat, Oman.

Keywords:
Oil viscosity; Heavy crude oil; Phase change material; Solar energy.

Highlights:
- *Effects of phase change material heated by solar energy on the flow assurance of heavy crude oil were investigated.*
- *Phase change material significantly improve viscosity reduction for heavy and light crude oils.*
- *The viscosity was 15 cP at 45°C and 6 rpm and 4 cP at 81°C.*

ARTICLE INFO
Article history:

Received	23 Dec. 2023
Received in revised form	09 Jan. 2024
Accepted	21 Apr. 2024
Final Proofreading	14 Nov. 2024
Available online	31 May 2025

Citation: Al-Doori G, Al Naamani OH, Chala GT. **Effect of Phase Change Material Heated by Solar Energy on the Flow Assurance of Heavy Crude Oil**. *Tikrit Journal of Engineering Sciences* 2025; **32**(2): 1941.
http://doi.org/10.25130/tjes.32.2.18

Corresponding author:
Ghassan Al-Doori
Al-Imam University College. Tikrit, Iraq.

Abstract: As the world's energy demand rises, crude oil and other hydrocarbon resources are required for different sectors to fulfill the global energy demand. Heavy crude oils are often difficult to transport due to their high viscosity and low mobility. Oil companies employ techniques including mixing, heating, and injection to lessen the viscosity of crude oil, as well as nanotechnology to lessen the viscosity. The present study aims to gradually reduce the viscosity of heavy crude oil by heating it using solar energy as clean energy. Solar water heater, PCM paraffin wax, heat exchangers, crude oil, and other materials were used. In this study, wax was used to store solar energy during the day and release it at night after sunset. It was observed that as the temperature increased, the viscosity fell, and vice versa. For instance, when using heavy crude oil, the viscosity rose to 8 cP at 45°C and 3 rpm and fell to 3 cP at 81°C. The viscosity was 15 cP at 45°C and 6 rpm and 4 cP at 81°C. A novel phase change material, such as wax and sand. In general, it is recommended to use solar energy systems integrated with latent thermal storage, i.e., phase change materials (organic), e.g., wax, and (inorganic), e.g., salts, or sensibly use non-phase change materials, e.g., sand ensure the provision to provide the necessary heat, to liquefy the oil (reduce viscosity), for facilitating its continuous flow through pipelines, without affecting the environment.

تأثير مادة متغيرة الطور (PCM) المسخنة بالطاقة الشمسية على ضمان تدفق النفط الخام الثقيل

غسان فاضل الدوري [١]، أسامة هلال النعيمي [٢]، جرمة ت. جاله [٢]

[١] كلية الامام الجامعة / تكريت – العراق.

[٢] الكلية الدولية للهندسة والإدارة / السيب / مسقط – سلطنة عمان.

الخلاصة

مع ارتفاع الطلب العالمي على الطاقة، تتطلب القطاعات المختلفة النفط الخام والموارد الهيدروكربونية الأخرى لتلبية الطلب العالمي على الطاقة. غالبًا ما تكون الزيوت الخام الثقيلة صعبة النقل بسبب لزوجتها العالية وانخفاض حركتها. تستخدم شركات النفط تقنيات تشمل الخلط والتسخين والحقن لتقليل لزوجة النفط الخام، بالإضافة إلى تقنية النانو لتقليل اللزوجة. تهدف الدراسة الحالية إلى تقليل لزوجة النفط الخام الثقيل تدريجياً عن طريق تسخينه باستخدام الطاقة الشمسية كمصدر للطاقة النظيفة. تم استخدام سخان المياه بالطاقة الشمسية، وشمع البارافينPCM ، والمبادلات الحرارية، والنفط الخام، ومواد أخرى. في هذه الدراسة، تم استخدام الشمع لتخزين الطاقة الشمسية خلال النهار وإطلاقها في الليل بعد غروب الشمس. لوحظ أنه مع زيادة درجة الحرارة، انخفضت اللزوجة، والعكس صحيح. على سبيل المثال، عند استخدام النفط الخام الثقيل، ارتفعت اللزوجة إلى ٨ سنتي بواز في ٤٥ درجة مئوية و٣ دورات في الدقيقة وانخفضت إلى ٣ سنتي بواز عند ٨١ درجة مئوية. كانت اللزوجة ١٥ سنتي بواز في ٤٥ درجة مئوية و٦ دورة في الدقيقة و٤ سنتي بواز في ٨١ درجة مئوية. مادة جديدة متغيرة الطور، مثل الشمع والرمل. بشكل عام، يُوصى باستخدام أنظمة الطاقة الشمسية المدمجة مع التخزين الحراري الكامن، أي المواد التي تتغير حالتها (العضوية)، مثل الشمع، و(غير العضوية)، مثل الأملاح، أو استخدام المواد غير المتغيرة الحالة بشكل معقول، مثل الرمل، لضمان توفير الحرارة اللازمة لتسييل الزيت (تقليل اللزوجة)، لتسهيل تدفقه المستمر عبر الأنابيب، دون التأثير على البيئة.

الكلمات الدالة: لزوجة الزيت، النفط الخام الثقيل، مادة متغيرة الطور، الطاقة الشمسية.

1.INTRODUCTION

Numerous applications of solar energy, i.e., sustainable energy sources, exist. Depending on how much latent heat is captured, one of the greatest methods for storing solar thermal energy is through phase change material [1]. In Spain and the US, more than ten large-scale power generation plants are operating and utilizing PCM technology [2]. Phase change materials are useful for static and dynamic thermal energy storage. The principle of its work is to withdraw and store heat in a latent form during the liquefaction process (its transformation from a solid to a liquid state) and release it when needed through the solidification process. PCM slurry analysis is microencapsulated with a crystallization/melting temperature of about 18°C and in a chilled ceiling test chamber [3]. In addition, phase change material (PCM) is used in construction to allow the release or storage of energy from internal loads or solar radiation. It is also essential to improve thermal comfort and reduce energy consumption [4]. Using phase change material is one of the most important ways to store thermal energy. In addition, it is used in latent thermal storage systems for solar engineering and heat pumps, as well as in spacecraft thermal control. Several PCM devices harden and melt at temperatures [5]. In addition, using PCM-powered heat sinks helps cool cell phones [6]. Energy storage is important and performed in several ways: mechanical methods, such as flywheels and compressed air; electrical methods, such as bilayer capacitors; and electrochemical methods [7]. The PCMs should be used to develop new energy storage devices to reduce the greenhouse effect. As latent heat of fusion, PCM stores heat 100 times more than the reasonable temperature. The main types of PCMs are fatty acids, paraffin wax, wet salts, and eutectic materials for inorganic and organic compounds as they melt at temperatures [8]. Using Solar Energy and PCM in solar water heaters (SWHs) has reduced 50 tons of carbon dioxide emissions in nearly 20 years. TES technology running on liquid and solid PCM devices with a solar thermal heating system absorbs more heat than regular solar water heaters. Solar water heaters enhance efficiency and avoid fluctuations in temperature inside the stored water. First, water heaters filled with PCMs at the bottom of the heaters. Therefore, the available energy in the storage system is less because of the PCM's low thermal conductivity. In solar energy applications, molten salt is used as a storage medium for thermal energy. While in solar energy applications and at medium temperatures between 200°C to 300°C, nitrates and their binary mixtures are considered a good phase change material (PCM) for their use [9]. PCM is divided into three classes based on its constituent materials: salt hydrate basis, water, and organic matter. PCM can also be available in PCM-encapsulated and raw PCM, i.e., not encapsulated in microcapsules. The two options differ depending on the body. Aqueous and inorganic PCMs cannot be encapsulated. PCM encapsulation provides an outer coating for the PCM core to prevent deterioration, contamination, and leakage. Encapsulation also adds strength to PCM. The coated phase change materials come in three forms: slurry, wet cake, and dry powder. Each has its advantages for inclusion or application over other materials. PCM is used in building materials, mattresses, and electronics. The benefits of PCM are numerous, including saving energy, cooling and heating at remote sites, and making electronic devices work better [10]. PCMs are isothermal; thus, they can operate at variable temperatures and provide a high density of energy stock [11]. Phase change material is used to improve the thermal performance and cold storage. Polyethylene glycol 400 (PEG400) phase change materials improve some projects' thermal performance. PCM is a material with a low melting point, and its phase changes by absorbing latent heat present in the system to maintain system temperature. In different systems, PCM is applied to increase thermal energy storage capacity. PCM is characterized by isothermal behavior during discharge and charging and has a high heat storage capacity. Furthermore, cooling and heating systems (TES) are essential for good performance in industrial processes. Desirable characteristics of the storage system are high-energy capacity for discharging and charging and high-energy storage density. Utilizing phase change material as the stockpiling joint is an effective and profoundly productive method using their enthalpy as a stockpiling instrument. In TES, PCM has many advantages; however, other forms of energy storage media have fewer advantages. Storage facilities in PCM are better than reasonable types of heat storage. PCM's narrow range in temperature at thermal energy discharge and charge times has earned it a distinctive ability that makes it suitable for applications in the smaller range at temperature changes [12]. Capturing and storing energy is challenging; however, phase change materials are ideal for thermal energy capture and storage. PCM devices act as batteries for thermal energy because they absorb thermal energy when the energy melts. They can be recharged by cooling them until they crystallize, and then stored energy is returned to the environment. In addition, without changing their thermal properties, PCMs can release and store thermal energy many times [13]. However, an emulsion was formed, and the practical level of reduction was at 30-50°C, at a high shear rate, and 70-75% oil content [14]. Several methods to reduce the viscosity of crude oil, including temperature, light oil concentration, and shear rate in viscosity behavior [15]. However, mixing heavy crude oil with a quantity of light crude oil is the best way to reduce viscosity [16]. When there is a direction electric field, the crude oil's viscosity is reduced in the direction of oil flow. When a high-voltage electric field is applied in the direction of the flow of waxy crude oil, the viscosity of the oil may decrease. The electric treatment increases the particles' aggregation and the wax crystals' size; however, the weak interaction between the wax particles is due to exposure to the electric field, which is the reason for the low viscosity [17]. High viscosity may cause difficulty in heavy crude oil transportation in pipelines. Paraffin and asphalting deposition, salt content, increased water content in the formation and corrosion issues [18]. One of the difficulties in transporting oils is their low mobility and high viscosity. Some methods for reducing the viscosity of crude oil include mixing, water, and heating in an annular flow and oil emulsion [19]. When mixing kerosene, naphtha, and light crude with oils, the results showed that heating reduced viscosity rapidly and that naphtha was the best type of mixture that reduced the viscosity of Nowruz and Serous crude oil to 200 cc, which is the viscosity of pipes using 15 and 5 volle% of naphtha [20]. Nanotechnology reduces the viscosity related to the electric field and works on types of crude oil, such as paraffin base oil and asphalt. The electric field is effective at low temperatures. After two seconds of applying the electric field, the viscosity significantly decreases, and the flow rate in the pipeline increases a lot. The technology consumes a small amount of energy and is useful in producing crude oil and marine and land transportation [21]. Despite the Sultanate of Oman having plenty of solar energy, the companies still suffer from the transfer of heavy crude oils. However, limited studies have been reported on using phase change materials powered by solar energy for the flow assurance of heavy crude oils. Therefore, the present study aims to utilize phase change material powered by solar energy for flow performance improvements. This method, while economical, would also reduce using environmentally non-friendly chemicals for flow assurance purposes.

2.MATERIALS AND METHODS

To understand how to reduce the viscosity of heavy crude oil, a new rig was built for operation in the International College of Engineering and Management (ICEM) in Al Seeb, Sultanate of Oman, in the second week of April. Solar water heater consists of three parts: a heat storage tank, vacuum tubes, and a support frame. The heat collected portion is the vacuum tubes covered by three layers: infrared-reflection layer, absorbance layer, and anti-reflection layer, which comprised two borosilicate glass tubes. The outside of the inner tube was coated with the stainless aluminum nitride layer, which can endure a temperature of up to 350°C. The coating absorbs sunlight exclusively (absorptance ≥0.92, emittance≤0.09, 80 °C). The main body of the SWH was towards the south direction and at an angle of 56°. There were two vessels in the setup. Each vessel had a capacity of 15 liters made from galvanized steel and insulated with a 5 cm insulation thickness to prevent heat losses. One is for wax and coil made from a copper tube 1.2 cm in diameter, and the other is for crude oil and copper coil. The domestic water pump of 0.37 kW, the max flow rate of 35 l/min, and the max head of 35 m were used in this study. Viscometer model 35 SA was used to measure the viscosity of crude oil. A Multi-channel thermometer model (Applent instruments AT4508 Multi-Channel Digital Temperature meter) and thermocouples type K were used. MECO solar power meter (Model: 936), a portable meter, was used for measuring solar power or solar irradiance. The water flow meter (Q) can be calculated using a vessel of a 600ml and a stopwatch, which was $\frac{600ml}{24s}$= 25ml/s. The mass flow rate can be calculated from [22]:

$$\dot{m} = \rho\, Q \tag{1}$$

where ρ is the density of water, and Q is the volume flow rate. Convection heat transfer mode is used to calculate the heat absorbed by water as it travels through the solar collector. The formula of heat absorbed by the water (Q_a) is given by [22]:

$$Q_a = \dot{m}\, C_p\, (T_2 - T_1) \tag{2}$$

where T_2 and T_1 refer to the outlet and inlet temperature of the water, and Cp refers to the specific heat of water, which is 4.18 kJ/kg. Calculating the length of the copper coil (L) using the empirical relations for mass-transfer coefficients is presented below [23]:

$$L = \frac{A}{2\pi r} \tag{3}$$

where A is the area, and r is the radius.
The area can be calculated as follows:

$$A = \frac{Q}{U\,\Delta T} \tag{4}$$

where Q is the heat transfer, U is the overall heat transfer coefficient, and ΔT is the temperature change. The overall heat transfer coefficient (U) is calculated by:

$$\frac{1}{U} = \frac{1}{hi} + \frac{1}{ho} \tag{5}$$

where h_i and h_o are the inside and outside heat transfer coefficients, respectively. The heat transfer coefficient for the inner pipe is given by:

$$h_i = \frac{Nuk}{D} \tag{6}$$

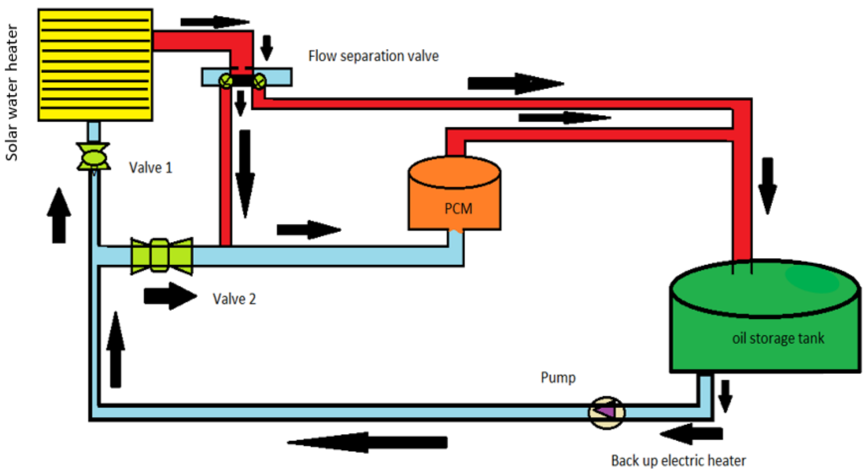
where D is the pipe diameter, k is the thermal conductivity of the fluid, and Nu is the Nusselt number. Nusselt number (Nu) can be determined from:

$$Nu = 0.023 Re^{0.8} \times pr^{0.4} \tag{7}$$

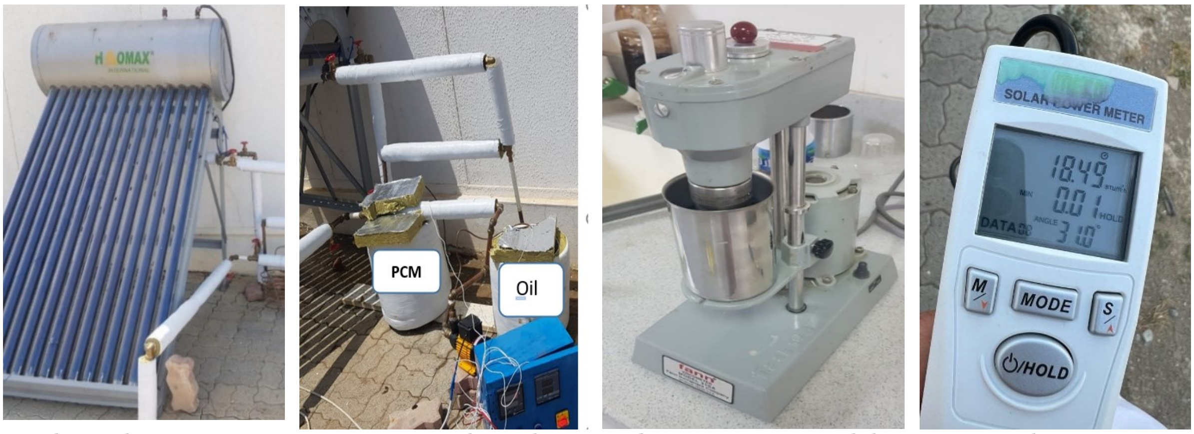
where Re is the Reynold number, and pr is the Prandtl number. The Reynold number is calculated from:

$$Re = \frac{\rho V D}{\mu} \tag{8}$$

where ρ is the density, V is the velocity, D is the diameter, and μ is the dynamic viscosity. Figures 1 (a-e) show the experimental setup used in the present study. The phase shifter is first connected to the SWH via a container with a circle-shaped tube. Adding water to the SWH to help them transmit energy to the container containing the PCM of 12 liters. Additionally, pipes connect the PCM container to the crude oil container of 12 liters. To control the phase change material between the two ends, add a pump to the circuit that connects the tank containing the phase change material and the vessel containing the crude oil. The mixer was combined with the crude oil-containing container with the phase change material. The tubes and containers were then covered with a heat insulator to preserve the thermal energy. The thermocouple and thermometer were then tested. The experiment utilized heavy and light crude oils on a different day. From eight in the morning to eight at night, experiments were conducted. Table 1 shows the studied PCM thermo-physical properties. The experimental work was divided into two parts. The first part was to run the system without activating the PCM vessel, meaning that the hot water from the SWH goes directly to the crude oil vessel (Heavy and light) crude oil. During that run, the readings of the thermocouples, the water flow rate, and at the same time, the samples of crude oil to measure the viscosity were recorded. The second part repeated the same experimental work by activating the PCM vessel, meaning that the hot water also passes through the PCM and crude oil vessels. The cost of the process of heating oil using solar energy is listed in Table 2.



(a)



(b) Solar Water Heater. **(c)** PCM and Crude Oil. **(d)** Viscometer Model 35 SA. **(e)** Solar Power Meter Model: 936.

Fig. 1 Experimental Setup: (a) Schematic Diagram, (b) Solar Water Heater, (c) PCM and Crude Oil, (d) Viscometer, and (e) Solar Power Meter.

Table 1 Thermo- Physical Properties of the PCM.

PCM	Quantity	Units
Melting point	46 and 68	°C
Boiling point	370	°C
Heat Fusion h_f	200-220	kJ/kg
Thermal Conductivity k	0.19 -0.35	W/m.K
Specific heat Cp	2.14–2.9	kJ/kg.K
Density ρ	Solid 0.76 Liquid 0.88	kg/l

Table 2 Cost of the Material Used in the Rig.

Item	Quantity	Price
Solar Water Heater	1	300$
Water Pump	1	70$
Copper tubes	25 M length	250$
PCM	12 liters	25$
Fittings	4	10$

3.RESULTS AND DISCUSSION

Before starting the experimental work, all thermocouples were calibrated with a standard mercury thermometer (MT). Table 3 compares the reading of the standard mercury thermometer and thermocouples type K. It is clear that the devices operated with a high accuracy, and the temperatures were very close to the mercury thermometer. In the experiment, cold water (a mixture of water and ice) was used the first time, then the water was heated, and temperatures were measured from time to time. Initially, temperatures in the thermocouples and MT started at 2°C. After a period, it gradually rose and reached approximately 7 °C. When the water was heated, the temperature reached 53 °C. At the end of the experiment, when boiling the water, the temperature reading was 100°C for MT and 100.8°C for the thermocouples, indicating that the temperatures in the thermocouple were very accurate and can be used in experiments. Figure 2 shows solar radiation with time. It was noticed that the maximum solar irradiance was 770 W/m², potentially heating the water to a higher temperature close to the boiling point.

Table 3 Calibration of Thermocouples.

Mercury Thermometer	Thermocouples		
	T1	T2	T3
2	2.2	2.1	2.1
7	7.3	7.2	7.1
12.5	13	12.9	12.8
17.5	17.9	17.2	17.6
32.5	33	32.4	32.3
46	46.4	46.2	46.5
53	53.3	53.1	53.2
66	66	66.2	66.2
74	74.5	74.4	74.2
90	90.6	90.2	90.3
100	100.5	100.8	100.6

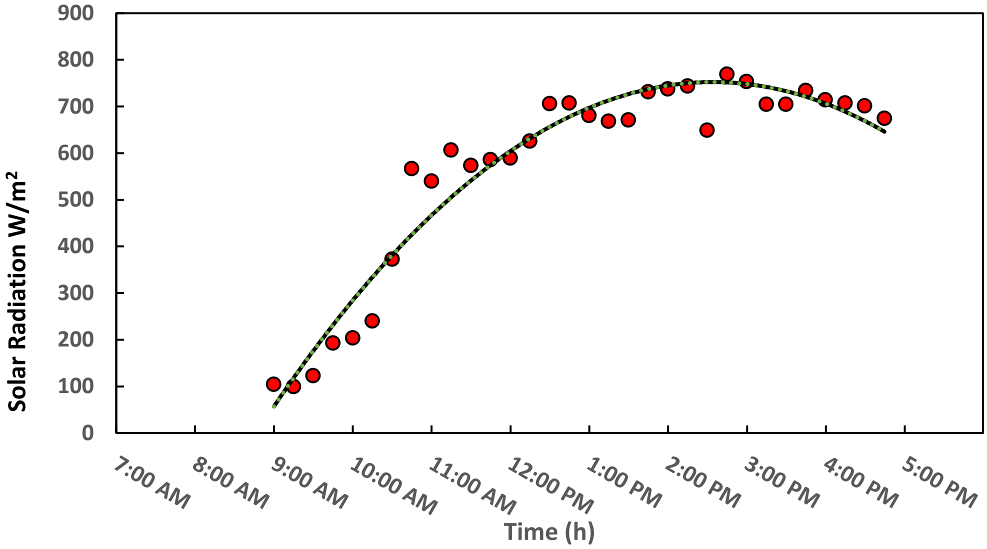


Fig. 2 Solar Radiation Average for Five Days Reading by MECO Solar Power Meter (Model: 936).

3.1.Part One Without Activating the PCM Vessel

Figure 3 shows the results of the temperature of heavy crude oil. It turned out that the temperature began to rise gradually from 8:00 in the morning, i.e., 40 °C. Between 12:00 and 14:00, the temperature of heavy crude oil reached its highest value, i.e., 70 °C. After that, it began to deteriorate gradually, and at 4:00 p.m., it reached 69 °C and then continued to decline until it reached 55 °C at 20:00. The gradual decrease in temperature was due to several reasons, among which the sun began to set. The temperature of solar panels and water began gradually decreasing. It was noted that the water temperature began to rise gradually in the morning from 08:00, which was 52 °C. Between 1:00 pm and 2:00 pm, it was noticed that the heavy crude oil's temperature reached its highest value, i.e., 81 °C, which began to decrease gradually until it reached 56 °C at 17:00. Therefore, after 05:00 pm, the solar panels were turned off, and the wax was used to heat the heavy crude oil. In addition, the solar panel temperature per hour is depicted. It was noted that the temperature ranges were between 27°C and 35°C. The recorded temperatures of the solar panels were close to each other. The temperature at 8:00 in the morning reached 28 °C; at noon, it reached 35°C; and in the evening, at 05:00 p.m., it reached 27 °C. Figure 4 shows the viscosity of crude oil at 3 rpm and 6 rpm under varying temperatures. It is noted that increasing temperature reduces the viscosity of heavy crude oil. Viscosity changes according to temperature. As shown in the previous figure, viscosity at 40 °C at 3 rpm was 8 °C and reduced to 2 CP at 71 °C. However, viscosity at 40 °C at 6 rpm was 15 cP and decreased to 4 cP at 71 °C. The decrease and increase in viscosity were due to the temperature. When the temperature increased, viscosity decreased, and vice versa.

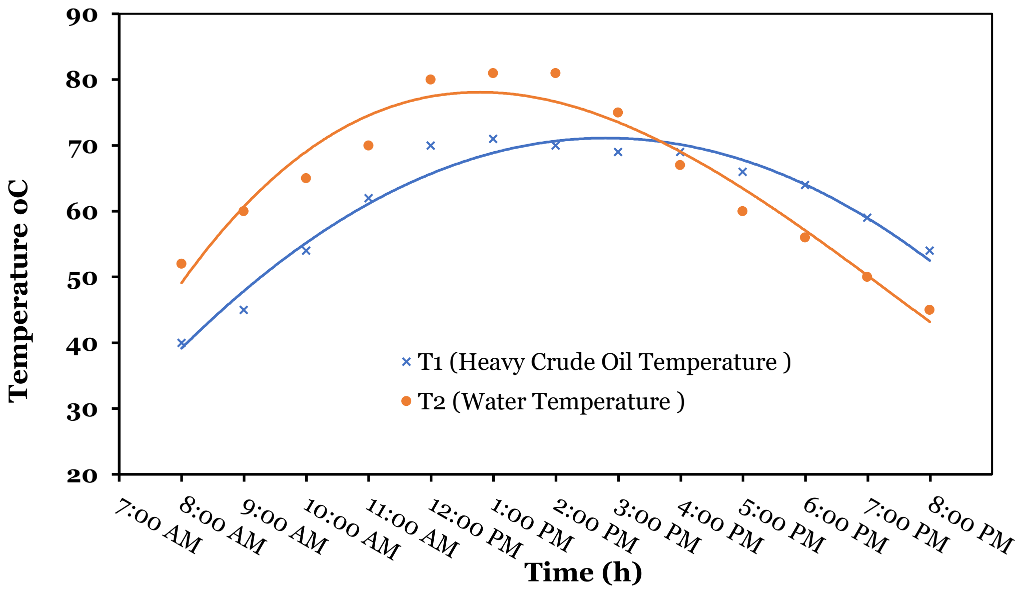


Fig. 3 Temperatures of Heavy Crude without Wax.

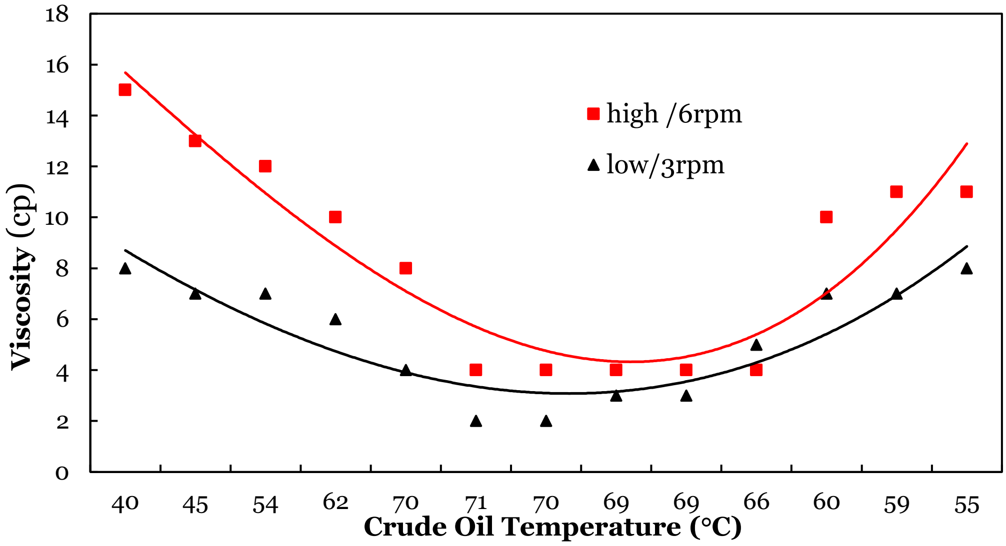


Fig. 4 Comparison of Viscosity 3 rpm and 6 rpm for Heavy Crude without Wax.

Figure 5 illustrates the light crude oil temperature results. It turned out that the temperature rose gradually in the morning, and at 08:00 A.M., it was 42 °C. However, from 1:00 P.M. until 2:00 P.M., it was noticed that the temperature of the light crude oil reached its highest temperature. It began to decline and reached at 05:00 P.M. 66 °C. Several hours later, the temperature at 08:00 P.M. reached 59 °C. Water temperature per hour is also shown. Water temperature increased gradually in the morning from eight in the morning to 52 °C. In addition, the highest temperature at 2:00 P.M. was 82 °C. The temperature decreased gradually until it reached 55 °C at 05:00 P.M., after turning off the solar panels, wax was used to heat the heavy crude oil. The temperature ranged between 30°C and 33°C. It was also noted that the recorded temperatures of the solar panels were close to each other. The temperature at 8:00 reached 30 °C. In addition, at 2:00 P.M., it reached 33°C, and at 5:00 P.M., it reached 30° C. Figure 6 shows the crude oil viscosity at 3 rpm and 6 rpm under varying temperatures. It was observed that increasing temperature reduced the viscosity of light crude oil. Viscosity changes according to temperature. Viscosity at 42°C at 3 rpm was 4 °C and decreased to 2 cP at 71°C. However, the viscosity at 42°C at 6 rpm was 5 cP and reduced to 3 cP at 71°C. The decrease and increase in viscosity were due to temperature. When temperature increased, the viscosity decreased and vice versa.

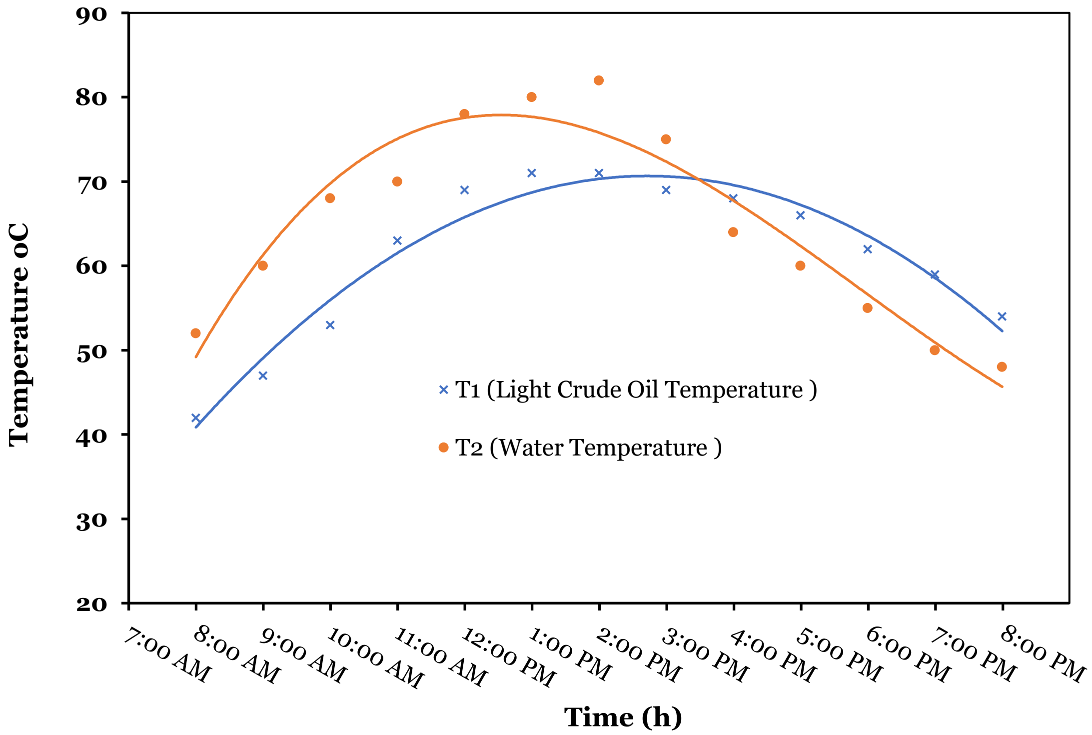


Fig. 5 Temperature Results for Light Crude Oil without Wax.

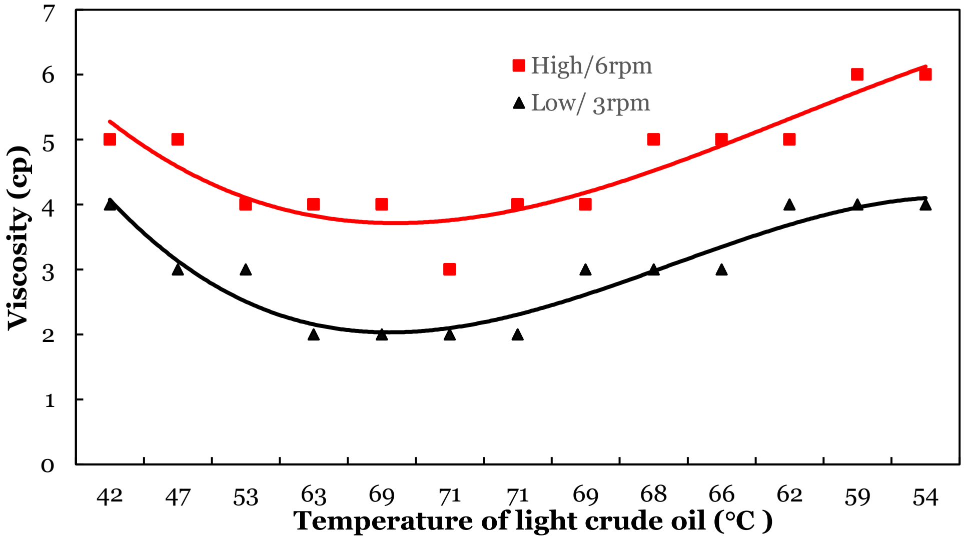


Fig. 6 Comparison of Viscosity 3 rpm and 6 rpm for Light Crude Oil without Wax.

3.2.Part Two with Activating the PCM Vessel

Figure 7 shows heavy crude oil temperature per hour. It also shows a gradual temperature rise, starting at 8:00 A.M. The temperature at 8:00 was 45 °C. At 01:00 P.M., the temperature of heavy crude oil reached its highest value and then began to decline at 03:00 P.M., reaching 74 °C. At 08:00 P.M., the temperature was 57 °C. The gradual decrease in temperature was due to several reasons, including the start of sunset; therefore, the solar panels and water temperatures gradually decreased. The heat the wax had stored in the morning was gradually lost with its use in the evening. The wax temperature began to rise at 8:00 A.M., and the wax temperature was 44°C. However, after several hours, at 01:00 P.M., the temperature became 84 °C. At 08:00 P.M., it was a 56°C. The reason for the gradual decrease in the temperature of the wax was that the stored energy was used in the morning and evening to reduce the crude oil viscosity. The wax began storing heat to reduce the viscosity of the crude oil. Moreover, after several hours of using it, the wax's temperature gradually decreased. The water temperature began to rise gradually in the morning from 80:00 A.M., reaching 52°C and reached the highest temperature at 1:00 P.M., where it reached 84°C. After that, it began to descend gradually in the evening when the sun began to set. At 05:00 P.M., it was 60°C. Therefore, after 05:00 P.M., solar panels could be turned off, and wax can be used to heat the heavy crude oil. The solar panel temperature ranged between 28°C and 32°C. The recorded temperatures of the solar panels were close to each other. The temperature at 08:00 A.M. reached 29 °C. In addition, at 01:00 P.M., it reached 32°C. At 05:00 P.M., it reached 28 °C. Therefore, after 05:00 P.M., the solar panels can be turned off and rely on wax to heat heavy crude oil.

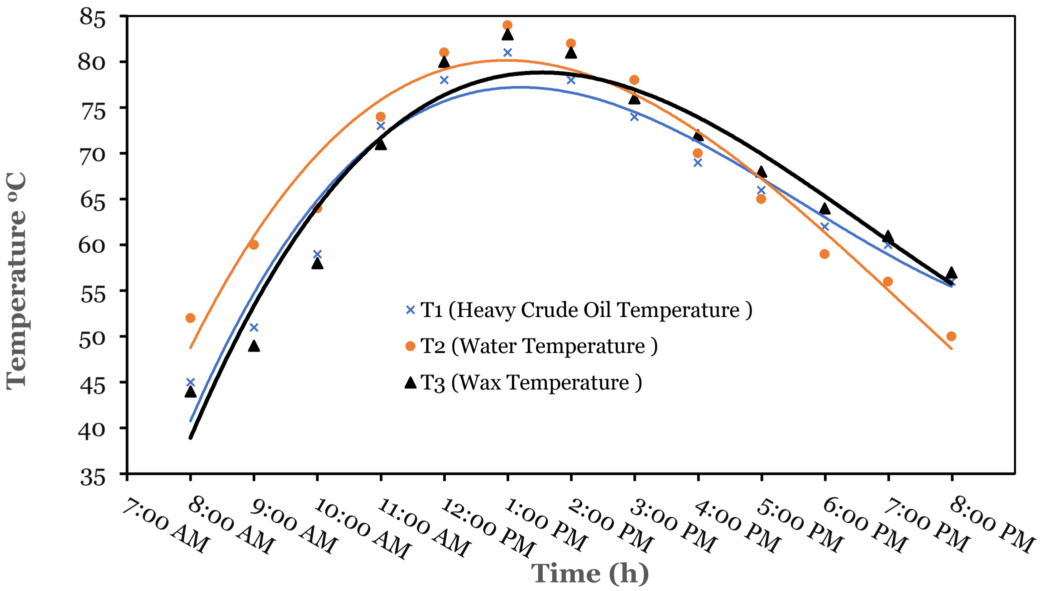


Fig. 7 Temperature of Heavy Crude Oil Per Hour.

Figure 8 shows the results of the viscosity of crude oil at 3 rpm and 6 rpm under varying temperatures per hour. Increasing the temperature reduced the viscosity of heavy crude oil. Viscosity changed according to temperature. Viscosity at 45°C at 3 rpm was 8cP and reduced to 3cp at 81°C. However, viscosity at 45°C at 6 rpm was 15cp and dropped to 4cp at 81°C. When the temperature increased, the viscosity decreased and vice versa.

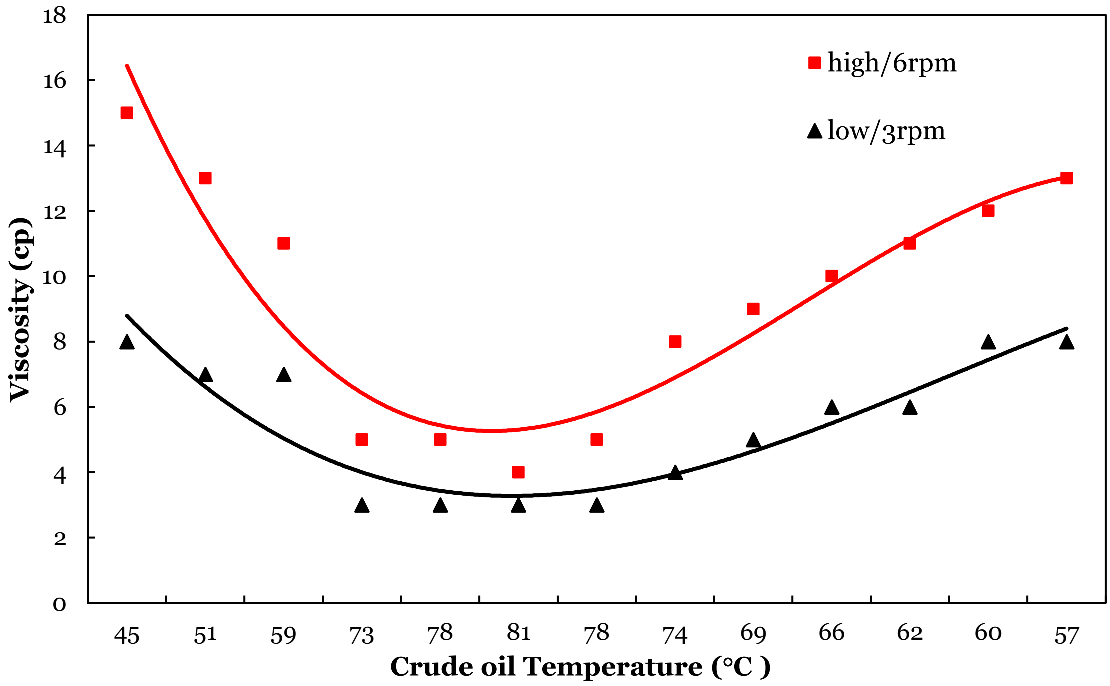


Fig. 8 Viscosity 3 rpm and 6 rpm for Heavy Crude Oil.

Figure 9 shows the light crude oil temperature per hour. The temperature gradually increased from 08:00 A.M. The temperature at 08:00 A.M. was 44°C. At 02:00 P.M., the temperature of the light crude oil reached its highest temperature, i.e., 81°C, and then started to decrease after 03:00 P.M. At 04:00 P.M., it reached 75°C. Several hours later, at 08:00 P.M., the temperature was 58°C. The gradual decrease in temperature was due to many reasons, including the onset of sunset and the lowering of the temperature of solar panels and water. The heat stored by the wax in the morning gradually decreased when used in the evening. The wax temperature began to rise at 08:00 A.M., and the wax temperature was 43°C; however, after several hours, at 02:00 P.M., the temperature became 82°C, and at 08:00 P.M., it was 57°C. The lower wax temperature was because the stored temperature in the morning was used to reduce the viscosity of crude oil in the evening. Wax in the morning began storing heat to reduce the viscosity of the crude oil in the evening, and after several hours of its use, the wax temperature began to drop. The water temperature began to rise gradually in the morning, starting at 8:00 A.M., reaching 52°C, and reaching the highest temperature from 12:00 P.M. until 02:00 P.M., when it reached 81°C. Until it gradually decreased in the evening, the temperature at 05:00 P.M. was 62°C. In addition, the hourly solar panel temperature results were also shown. The temperature ranged between 27°C and 32°C. The temperature at 08:00 A.M. reached 27°C. In addition, at noon, it reached 32°C, and at 5:00 p.m., it reached 27 °C. Figure 10 shows the viscosity of light crude oil at 3 rpm and 6 rpm under varying temperatures and measured per hour. It was observed that increasing the temperature would reduce the viscosity of the heavy crude oil. Viscosity changes according to temperature. The viscosity at 44°C at 3 rpm was 4 cP and reduced to 1 cP at 81°C. Viscosity at 44°C at 6 rpm was 5 cP and decreased to 3 CP at 81°C. Viscosity decreases and increases with temperature. When temperature increased, viscosity decreased. Figure 11 compares the heavy crude oil with and without PCM. It can be clearly observed that heavy crude oil with PCM performed better than that without wax. An almost similar trend was also observed regarding the temperature of light crude oil with and without PCM, as seen in Fig. 12. Light crude oil with PCM had a better flow assurance performance over time.

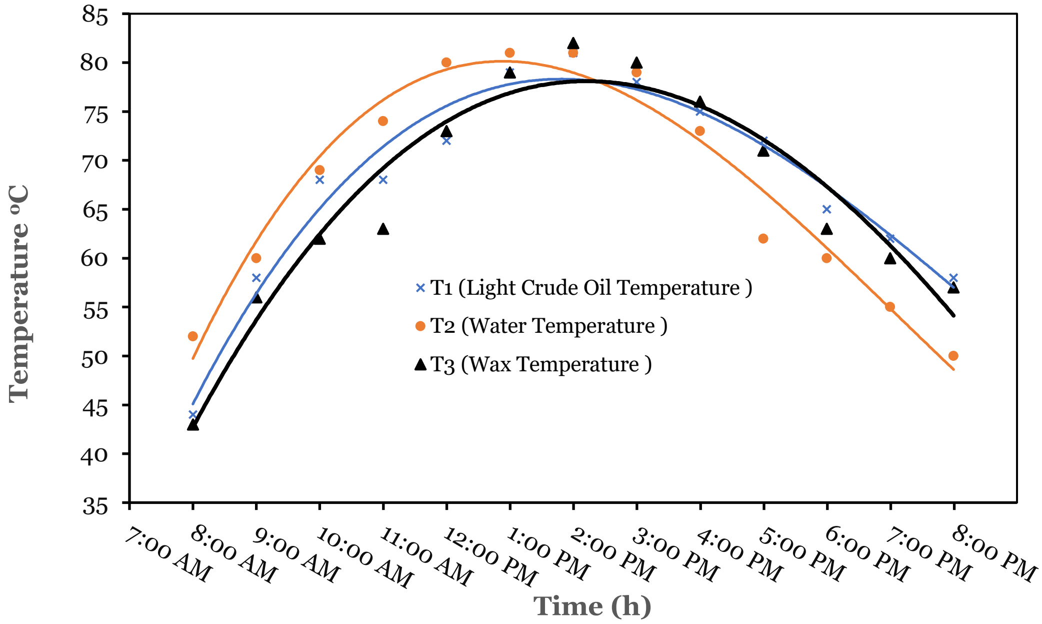


Fig. 9 Temperature of Light Crude Oil Per Hour.

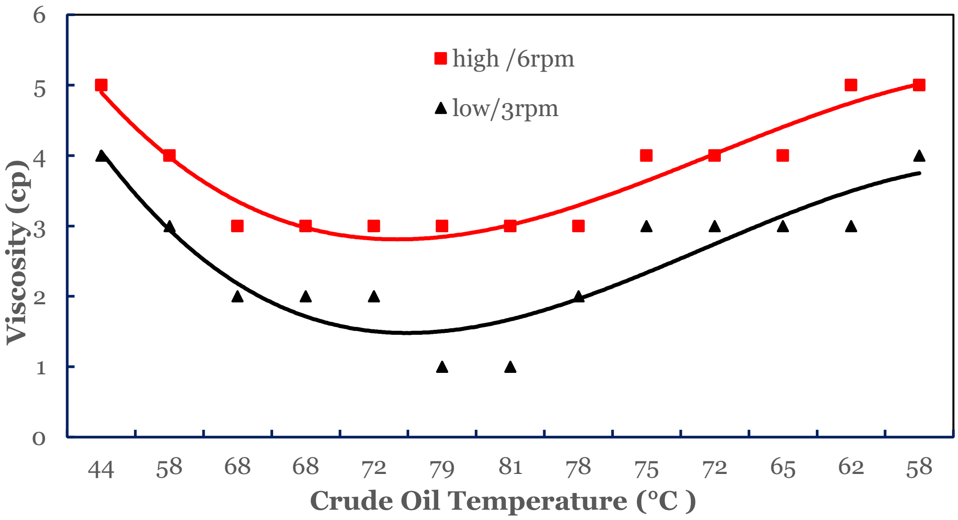


Fig. 10 Viscosity 3 rpm and 6 rpm for Light Crude Oil Per Hour.

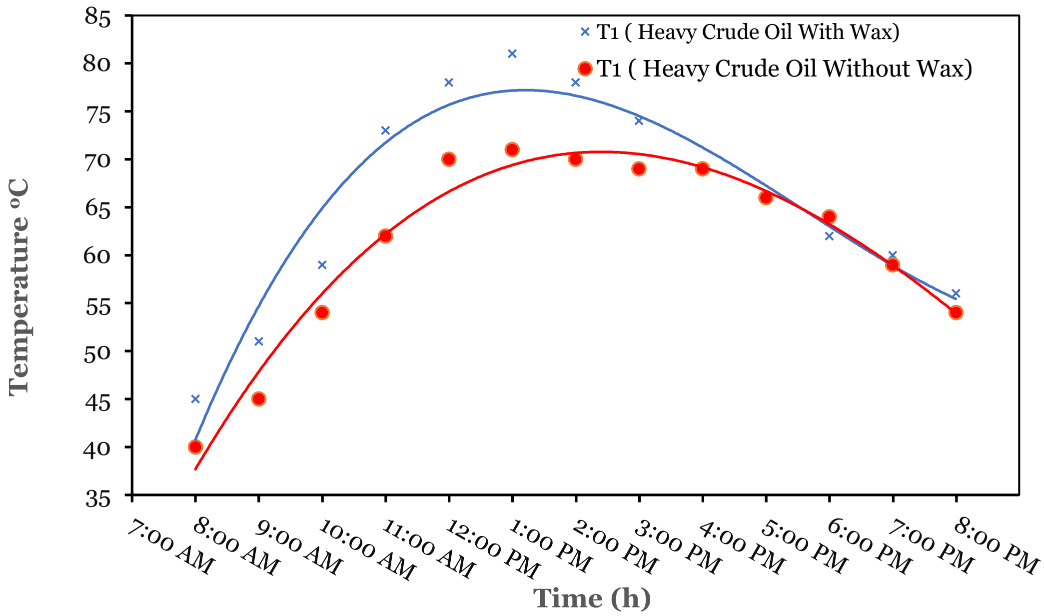


Fig. 11 Comparison between the Temperature of Heavy Crude Oil with PCM and without PCM.

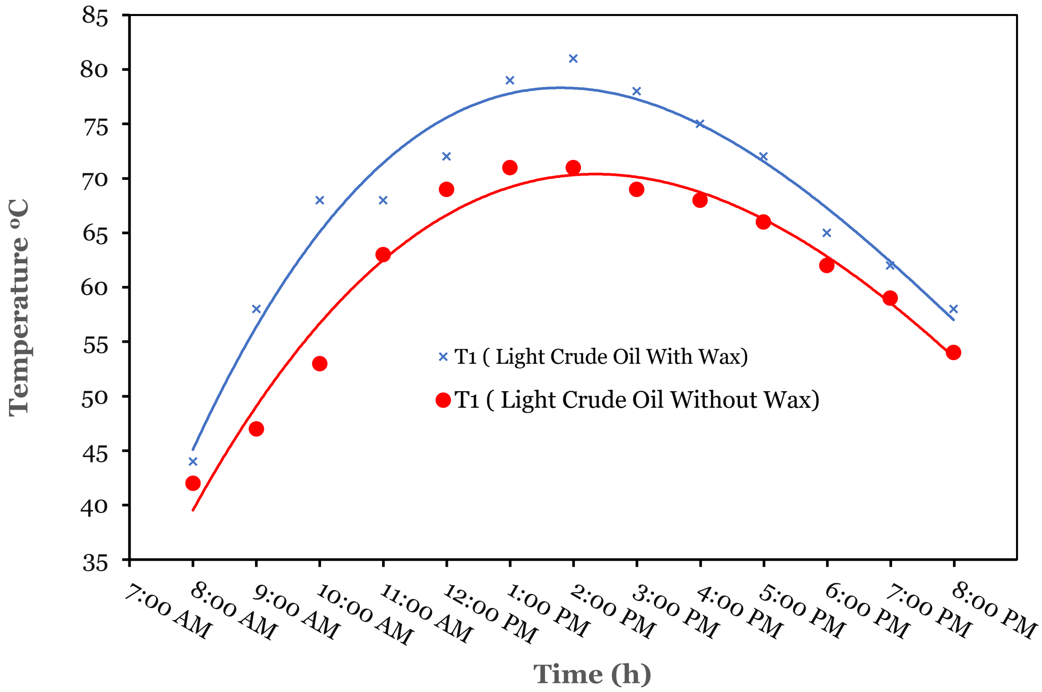


Fig. 12 Comparison between the Temperature of Light Crude Oil with PCM and without PC.

4. CONCLUSIONS

Numerous methods can be used to reduce the viscosity of crude oil. The present research aims to use solar energy to lower the viscosity of heavy crude oil. Additionally, wax was used to store energy for usage at night. Thermocouples were used to measure wax, crude oil, and water temperatures. Viscosity was measured with a viscometer. Experiments on light and heavy crude oils were conducted. It was observed that the experiments produced good results since crude oil's viscosity decreased. Wax also can store energy for the morning. For heavy crude oil, the viscosity rose to 8 cP at 45 °C and 3 rpm and fell to 3 cP at 81 °C. The viscosity was 15 cP at 45 °C and 6 rpm and 4 °C at 81 °C. Using a novel phase change material, such as wax and sand, is recommended in the future. This technology helps reduce the viscosity of crude oil and improves the flow assurance of heavy crude oil in transportation pipelines. Using solar energy in this field would have more benefits without negative environmental effects.

ACKNOWLEDGEMENTS

The authors would like to thank the International College of Engineering and Management (ICEM) for the support and facilities provided.

NOMENCLATURE

Cp	Specific heat capacity
D	Pipe diameter
h	Convective heat transfer coefficient
k	Thermal conductivity of the fluid
MT	Mercury Thermometer
Nu	Nusselt number
PCM	Phase change material
Pr	Prandtl number
Q	Volume flow rate
Qa	Heat absorbed by the water
Re	Reynolds number
SWH	Solar water heater
T	Temperature
U	Overall heat transfer coefficient
$\dot{m}$	Mass flow rate
ρ	Density of water

REFERENCES

[1] Kumar N, Gupta SK. **Progress and Application of Phase Change Material in Solar Thermal Energy: An Overview.** *Materials Today: Proceedings* 2021; **44**:271–281.

[2] Delgado JMPQ, Martinho JC, Sá AV, Guimarães AS, Abrantes V. **Thermal Energy Storage with Phase Change Materials.** *Springer International Publishing*; 2019.

[3] Griffiths PW, Eames PC. **Performance of Chilled Ceiling Panels Using Phase Change Material Slurries as the Heat Transport Medium.** *Applied Thermal Engineering* 2007; **27**(10):1756–1760.

[4] Kuznik F, Virgone J, Noel J. **Optimization of a Phase Change Material Wallboard for Building Use.** *Applied Thermal Engineering* 2008; **28**(11–12):1291–1298.

[5] Sharma A, Tyagi VV, Chen CR, Buddhi D. **Review on Thermal Energy Storage with Phase Change Materials and Applications.** *Renewable and Sustainable Energy Reviews* 2009; **13**(2):318–345.

[6] Setoh G, Tan FL, Fok SC. **Experimental Studies on the Use of a Phase Change Material for Cooling Mobile**

Phones. *International Communications in Heat and Mass Transfer* 2010; **37**(9):1403–1410.

[7] Vakhshouri AR. **Paraffin as Phase Change Material.** *Paraffin Overview* 2020; 1–23.

[8] AL-Ataby MJA. **Phase Change Materials for Thermal Energy Storage.** *Journal of Petroleum Research and Studies* 2012; **3**(1): 69-92.

[9] Xiao X, Zhang P, Li M. **Experimental and Numerical Study of Heat Transfer Performance of Nitrate/Expanded Graphite Composite PCM for Solar Energy Storage.** *Energy Conversion and Management* 2015; **105**:272–284.

[10] Du K, Calautit J, Wang Z, Wu Y, Liu H. **A Review of the Applications of Phase Change Materials in Cooling, Heating and Power Generation in Different Temperature Ranges.** *Applied Energy* 2018; **220**:242–273.

[11] Mofijur M, Mahlia TMI, Silitonga AS, Ong HC, Silakhori M, Hasan MH, Rahman SA. **Phase Change Materials (PCM) for Solar Energy Usages and Storage: An Overview.** *Energies* 2019; **12**(16):3167.

[12] TK G, Raj V. **Use of Phase Change Material (PCM) for the Improvement of Thermal Performance of Cold Storage.** *MOJ Current Research & Reviews* 2018; **1**(2):49–61.

[13] Rashid FL, Al-Obaidi MA, Dulaimi A, Mahmood DMN, Sopian K. **A Review of Recent Improvements, Developments, and Effects of Using Phase-Change Materials in Buildings to Store Thermal Energy.** *Designs* 2023; **7**(4):90.

[14] Yaghi BM, Al-Bemani A. **Heavy Crude Oil Viscosity Reduction for Pipeline Transportation.** *Energy Sources* 2002; **24**(2):93–102.

[15] Chala GT, Sulaiman SA, Japper-Jaafar A. **Flow Start-Up and Transportation of Waxy Crude Oil in Pipelines: A Review.** *Journal of Non-Newtonian Fluid Mechanics* 2018; **251**:69–87.

[16] Hasan SW, Ghannam MT, Esmail N. **Heavy Crude Oil Viscosity Reduction and Rheology for Pipeline Transportation.** *Fuel* 2010; **89**(5):1095–1100.

[17] Huang Q, Li H, Zhuang Y, Ding Y, Ma C, Chen C, Zhang J. **Reducing Viscosity of Waxy Crude Oil with Electric Field Perpendicular to Oil's Flow Direction.** *Fuel* 2021; **283**:119345.

[18] Martínez-Palou R, de Lourdes Mosqueira M, Zapata-Rendón B, Mar-Juárez E, Bernal-Huicochea C, de la Cruz Clavel-López J, Aburto J. **Transportation of Heavy and Extra-Heavy Crude Oil by Pipeline: A Review.** *Journal of Petroleum Science and Engineering* 2011; **75**(3–4):274–282.

[19] Cavicchio CA, Biazussi JL, de Castro MS, Bannwart AC, Rodriguez OM, de Carvalho CH. **Experimental Study of Viscosity Effects on Heavy Crude Oil-Water Core-Annular Flow Pattern.** *Experimental Thermal and Fluid Science* 2018; **92**:270–285.

[20] Homayuni F, Hamidi AA, Vatani A. **An Experimental Investigation of Viscosity Reduction for Pipeline Transportation of Heavy and Extra-Heavy Crude Oils.** *Petroleum Science and Technology* 2012; **30**(18):1946–1952.

[21] Tao R, Tang H. **Reducing Viscosity of Paraffin Base Crude Oil with Electric Field for Oil Production and Transportation**. *Fuel* 2014; **118**:69–72.

[22] Holman JP. **Heat Transfer**. McGraw-Hill; 2010.

[23] Gilliland ER. **Diffusion Coefficients in Gaseous Systems**. *Industrial & Engineering Chemistry* 1934; **26**(6):681–685.