International Journal of Chemical Studies 2019; 7(5): 732-738

International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
IJCS 2019; 7(5): 732-738

Received: 11-07-2019
Accepted: 15-08-2019

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Study on behaviour of thermal energy storage materials under conventional and solar heating systems

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Abstract
Milk is a highly perishable commodity and needs quick processing to prevent growth of microorganisms. Milk processing mainly contains heating and cooling operations and for most of the heating operations, steam is used as a heat transfer fluid. But the increasing energy demand leads to search for alternative renewable energy resources. Sun energy is highly efficient, free to use and does not harm the environment. A comparative study was done to select best heat transfer material for heating operations in milk processing. During the study, different energy storage materials viz. thermal fluids and phase changing material (PCM) in the form of salts were investigated to check their thermal profile, engineering characteristics viz. thermal expansion, melting point, smoke point etc. were evaluated. Sensible heat energy storage of thermal fluids namely; paraffin oil (light), silicon oil and phase changing salts namely; acetamide, magnesium chloride hexahydrate were analyzed for their heat absorption and thermo-physical properties. Among these four materials, paraffin oil was found as highest thermal energy absorbing material. The phase changing salts has more heat storage density as they absorb the heat in the form of latent heat. This leads to the storage of thermal energy for a longer period, once the salts are charged by heating but maximum heat energy was absorbed by paraffin oil (276 °C) surging ahead of silicon oil (260 °C). Peak temperature achieved by these oils is more than sufficient to cover the entire range of heating operations required in dairy process industries.

Keywords: thermal oils, PCM, thermal energy storage, milk

Introduction
With increasing population, there is a huge increase in energy demand which is fulfilled with both renewable and non-renewable energy sources. In India, only 28% of energy demand is met with renewable energy resources and rest is met from non-renewable sector which automatically results in huge emission of carbondioxide. Shortage of fossil fuels, associated ill effects of use of fossil fuels on environment and ever increasing demand for energy compels us to shift towards renewable energy resources like solar energy, wind energy, geothermal energy, tidal energy, biomass etc. as these energy resources are free, anti-polluting and anti-toxic to the environment. Among these energy resources, solar energy has a great scope in a country like India where sun shines in abundance. India gets around 5-7 KW/m^2 of sunshine for about 300-320 days per year (Desai *et al.* 2013, Sharma *et al.* 2012) [5, 12]. In addition, energy storage can help to save the premium fuels and also reduces the wastage of conventional energy.

A lot of solar technologies have been developed like solar photovoltaic cells, solar concentrators, etc. Photovoltaic cells can directly convert the light or optical energy into electricity whereas solar concentrators, depending upon the type of concentrator are capable in attaining temperature ranging from 120°-400 °C. Sun oriented energy can be used for electricity, transportation, cooking food, heating water etc. (Franco *et al.* 2008, Mekhilef *et al.* 2011, Bhave 2012, Chopde *et al.* 2016, Sharma *et al.* 2016, Jaglan *et al.* 2018) [6, 9, 3, 4, 14, 7]. The main problem arises when there is cloudy environment and other problem associated with the use of solar energy is that its availability varies with time (Bajpai 2012) [2]. The most efficient way to overcome this problem is to use some thermal energy storage material (Senthil and Cheralathan 2017) [13]

Thermal energy storage can be achieved either by sensible heat storage or latent heat storage. Latent heat energy can be stored in phase changing materials (PCM) like honey wax, acetamide, acetinalide, paraffin wax etc. Also, there are many sensible heat storage thermic oils which are used for storage of high degrees of temperature like paraffin oil, silicon oil, therminol 55, glycol, stearic acid etc. (Singh 2017, Singh *et al.* 2018) [7, 15]. Stored heat energy can be used for many heating operations in process industries. Currently, PCM's are mainly used in heat pumps, solar and spacecraft thermal control applications. Thermal oils are mainly used in automotive, marine and military applications across the world. Oils are also being utilized in piston pumps, processing equipments, compressors, gears etc. In PCM's, a continuous supply of heat energy leads to breakage of chemical bonds present in the phase changing materials which leads to change of solid phase into liquid phase. Phase changing is an endothermic process. The phase changing materials and thermic oils can be used for thermal heat storage when excess sunshine is available and can be used in the time when sunshine is not available in plenty.

Storage of solar energy can give a new solution to process unsafe milk at farm level. This can help in environment conservation and cost reduction. Solar energy can help in milk pasteurization at remote areas and in village communities where electricity and gas are not available (Atia *et al.* 2011) [1]. Solar energy can be used for milk pasteurization (Franco *et al.* 2008) [6] as well as milk sterilization (Jaglan 2018) [7].

Materials and method

Selection of thermal energy storage (TES) materials

Four heat transfer materials namely acetamide, magnesium chloride hexahydrate, paraffin oil, silicon oil were purchased from Alpha Chemika Pvt. Ltd., Mumbai. The selection was made on the basis of review of literature of previous research works and physio-chemical properties like specific heat, boiling point, melting point etc. Various trials were conducted with paraffin oil, silicon oil, acetamide and magnesium chloride hexahydrate to observe smoke point, boiling point, melting point, maximum temperature attained, rate of heating and rate of cooling.

Fig 1: Silicon oil

Fig 2: Paraffin oil

Fig 3: $MgCl_2.6H_2O$

Fig 4: Acetamide

Preliminary trials of heating the thermal energy storage (TES) materials

To determine the time temperature behavior of these TES materials, 2 liter of each thermal oils (paraffin oil and silicon oil) and 2 kg of each salt (acetamide and magnesium chloride hexahydrate) was taken in a mild steel vessel and heat was supplied using a gas burner. Temperature was observed after every 5 minutes to observe the increase in temperature. Decrease in temperature of fluid represented significant reduction in the temperature stability after achieving the maximum temperature. The smoke point and melting temperature was also noted as per the sensory procedure.

Solar heating of thermal energy storage materials

After observing the required properties of all the four thermal energy storage materials, the materials paraffin oil and silicon oil were found suitable as base materials in heating operations. These were heated in solar parabolic concentrator to check for the solar thermal profile of selected oils in comparison with thermal profile of water because mainly hot water or steam is used as a heat transfer medium in most of the dairy processing operations. The temperature stability was observed by stopping the supply of heat and temperature drop was noted till it becomes constant.

The solar parabolic concentrator works on the principle of concave lens. The solar parabolic concentrator focuses all the parallel sun rays to a particular point called focal point. The solar parabolic concentrator mainly consists of reflecting aluminum alloy sheet, base support, frame support and manual sun tracking system. A mild steel vessel was designed according to the design parameters of solar concentrator and developed vessel was placed at the focal point of concentrator to absorb the radiation heat. The vessel was painted black to absorb more heat from the sun. The vessel consists of pressure gauge (least count of 0.5 Kg/cm^2), safety valve and a temperature gauge (with least count 2.5 $^{\circ}C$) to monitor pressure, safety and temperature respectively. The safety valve of this vessel starts functioning if pressure inside vessel is above 4 Kg/cm^2 (Jaglan *et al.* 2018) [8]. Two liter each of paraffin oil, silicon oil and water was filled in the vessel and this vessel was then placed in the focal point of concentrator. Initial temperature and pressure of thermic oils were noted from the temperature and pressure gauge, respectively. Temperature and pressure of thermal oils was recorded at an interval of five (5) minutes, till a constant temperature is reached. Final quantity of remaining oil was collected and increase in volume of oils was recorded. The procedure was repeated to check the reheating of oils.

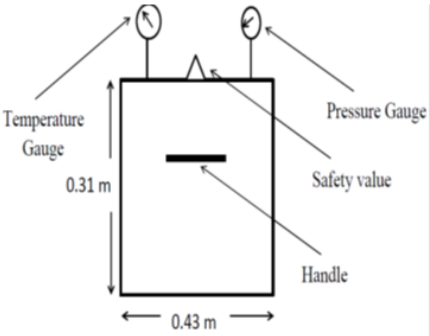

Fig 5: Mild steel pressure vessel

Fig 6: Solar Parabolic dish

Thermal expansion

It was important to check the increase in volume of thermic oils after heating to decide the space required and proper quantity which should be taken in the vessel. To determine maximum attained temperatures. Volume was noted before heating and after heating the oils and the difference between the volumes was simply calculated.

Results and discussion

Preliminary study for properties of heat transfer materials

It was important to study various properties of heat transfer materials for their selection. To start with, four heat transfer materials namely acetamide, magnisium chloride hexahydrate, paraffin oil and silicon oil were selected. The selection was based on the basis of previous researches and properties like specific heat, price and availability. Value of specific heat was: silicon oil 1.09 KJ/Kg K, paraffin oil 2.13 KJ/Kg K, Acetamide 1.94 KJ/Kg K and magnesium chloride hexahydrate 1.34 KJ/Kg K. Specific heat is the amount of heat required for one degree rise in temperature of unit mass of substance. Gas heating was done for all the four thermal energy storage materials and their properties like maximum attained temperature, rate of heating, rate of cooling, smoke point, melting point were studied. It was found that paraffin oil attains maximum temperature of 276 °C surging ahead of silicon oil 260 °C, acetamide 194 °C, magnesium chloride hexahydrate 176 °C as shown in table 1. On cooling, there was crystal formation in case of phase changing salt magnesium chloride hexahydrate whereas there was no such problem in case of paraffin oil and silicon oil. Also, acetamide produced very toxic and pungent smoke which can harm the lungs, liver and can cause breathing problems Also, the mixtures were made by mixing different proportions of oils with phase changing salts and were heated but no significant results were found. The heating of these mixtures created a lot of smoke and very pungent smell. When mixtures were made, there was crystal formation in case of magnesium chloride hexahydrate instead of melting and the mixtures produced a lot of smoke. Also, it was very difficult to perform the experiment in such smoky and smelly conditions. It also causes problem in storage and reheating as shown in Fig. 7. From the analysis of properties of thermal energy storage materials, it was observed that materials having higher boiling point, higher smoke point should be selected. Keeping all the desirable properties, paraffin oil and silicon oil were found the best heat transfer materials when gas heating was done. The observed physiochemical properties can be shown in table 1. Fig. 8 to 10 show that paraffin oil and silicon oil are better thermal energy storage materials than phase changing salts in terms of maximum attainable temperature as well as smoke point. The thermic oils produced smoke at very high temperature as comparative to the phase changing salts and the mixtures of PCM and thermic oils as shown in table 1.

Fig. 7: Mixtures of oils and salts after heating

Table 1: Thermo physical properties of heat transfer materials

Materials	Maximum temperature (^0C)	Rate of rise (^0C/minute)	Rate of cooling (^0C/minute)	Smoke point (^0C)	Melting Point (^0C)
Paraffin oil	276	16	2.92	215	Already liquid at room temperature
Silicon oil	260	19	1.81	180	Already liquid at room temperature
Acetamide	194	9	3.12	127	81
Magnesium chloridehexahydrate	179	11	3.68	131	119
Acetamide+Paraffin oil	178	14	2.45	152	77
Acetamide+Silicon oil	173	12	2.7	140	98
Magnesium chloride hexahydrate+Paraffin oil	174	15	2.6	138	Cluster formation
Magnesium chloride hexahydrate+Silicon oil	168	16	2.99	135	Cluster formation

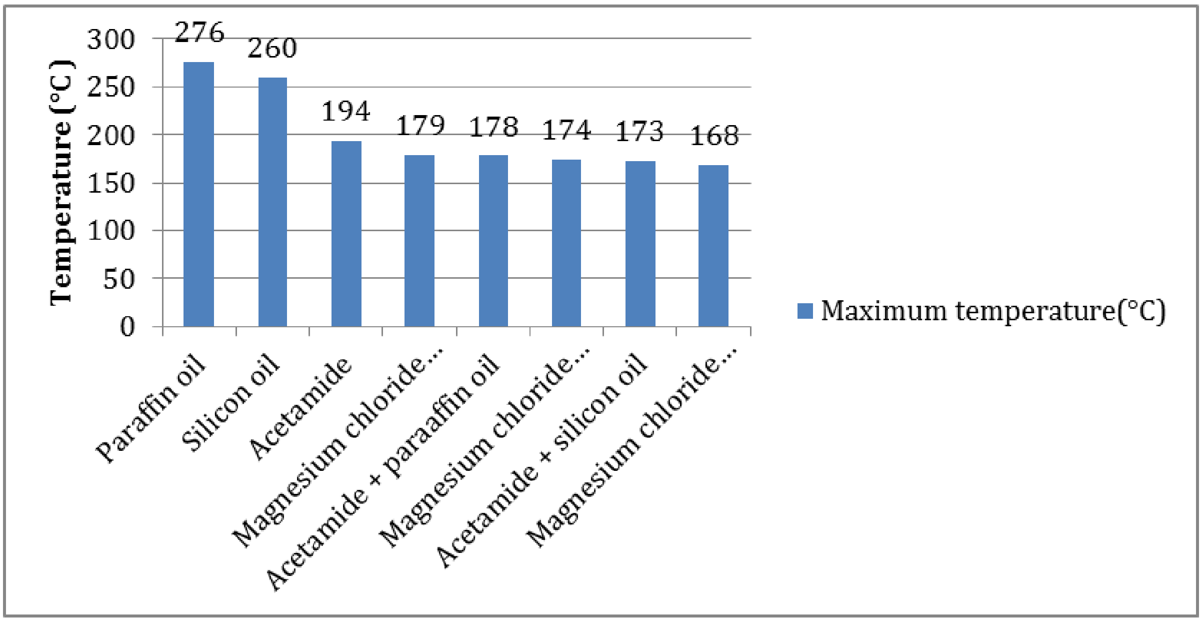

Fig 8: Maximum temperature attained by heat transfer materials using gas heating.

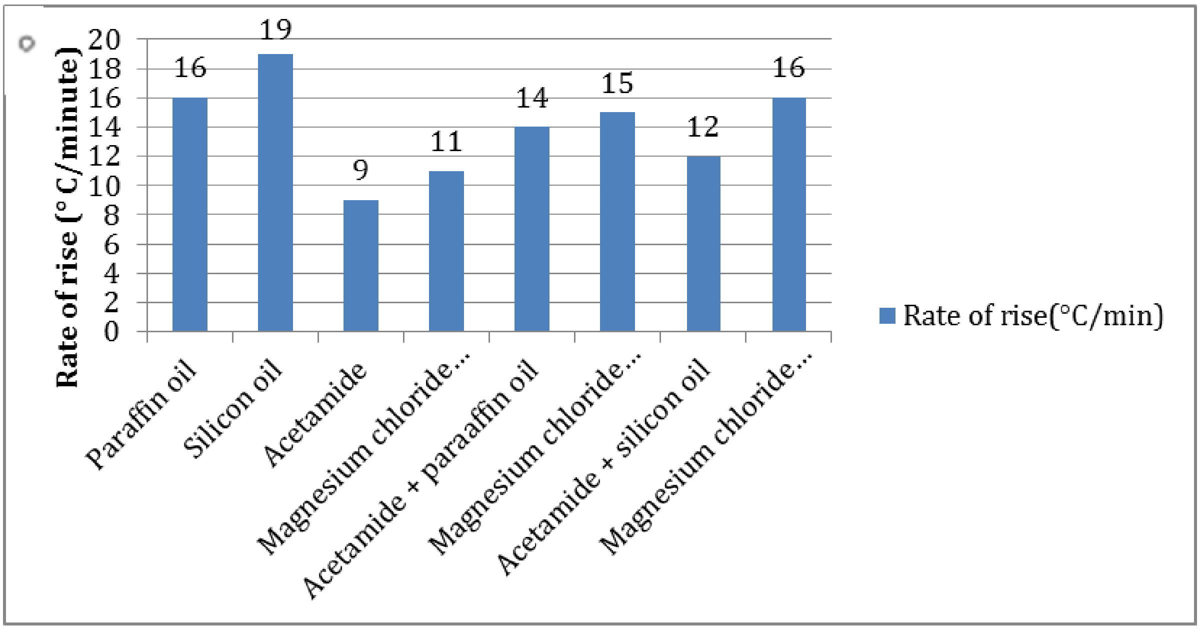

Fig 9: Comparative rate of heating for different heat transfer materials

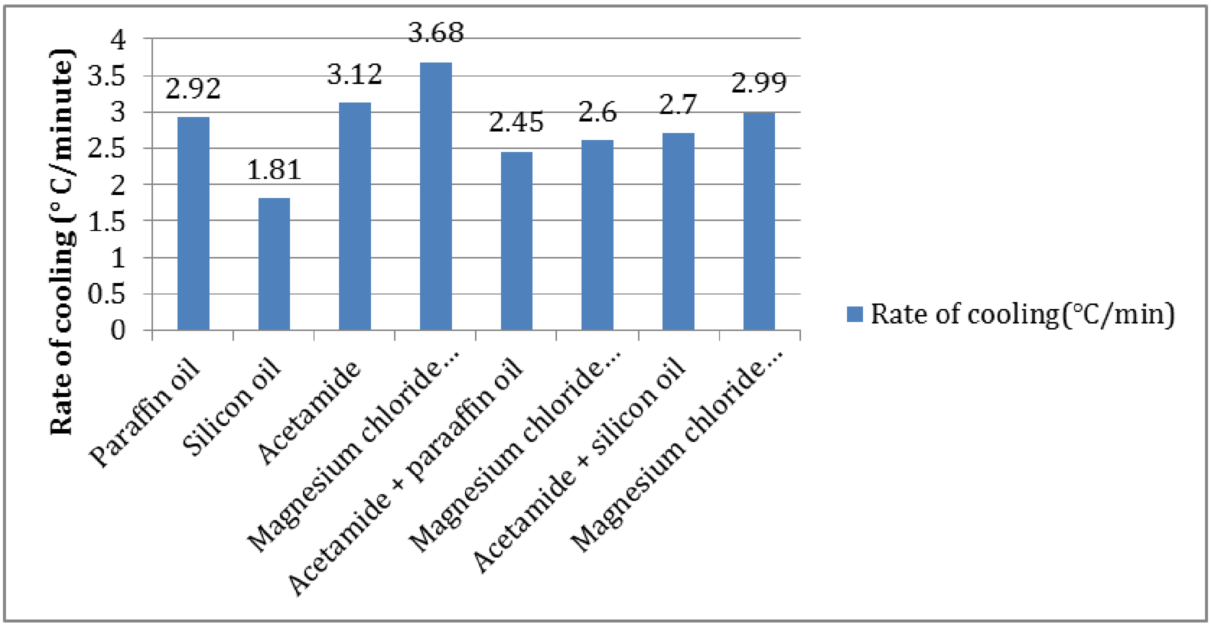

Fig 10: Comparative rate of cooling for different heat transfer materials

Solar heating of paraffin oil and silicon oil

Comparative study of Paraffin oil, silicon oil in comparison with water was done to check their temperature profile as shown in figure 11 and figure 12. The rate of rise of temperature of paraffin oil in comparison with silicon oil can be seen in figure 13. Also, Table 2 shows that under one present setup maximum temperature attained in paraffin oil, silicon oil and water were 186 °C, 179 °C, 150 °C respectively. There was pressure formation in case of water and maximum steam pressure noted was 4Kg/cm^2 whereas there was no vapor pressure created in case of paraffin oil and silicon oil even at such high temperatures. Between these two thermic oils, paraffin attained higher temperature than that of silicon oil. On heating, the increase in volume of silicon is higher than that of paraffin oil due to which it will give more expansion. Also, rate of cooling of paraffin oil is also higher than that of silicon oil, which is desirable, as it will act as a better heat transfer medium. The rate of rise of temperature is also higher in case of paraffin oil. So, Paraffin oil is found best for solar heating applications.

Table 2: Properties of heat transfer materials using solar heating

Name of oils	Maximum attained temperature	Increase in volume (ml/liter)	Time taken (minutes)
Paraffin oil	186 °C	70	55
Silicon oil	179 °C	115	45
Water	150 °C	-	100

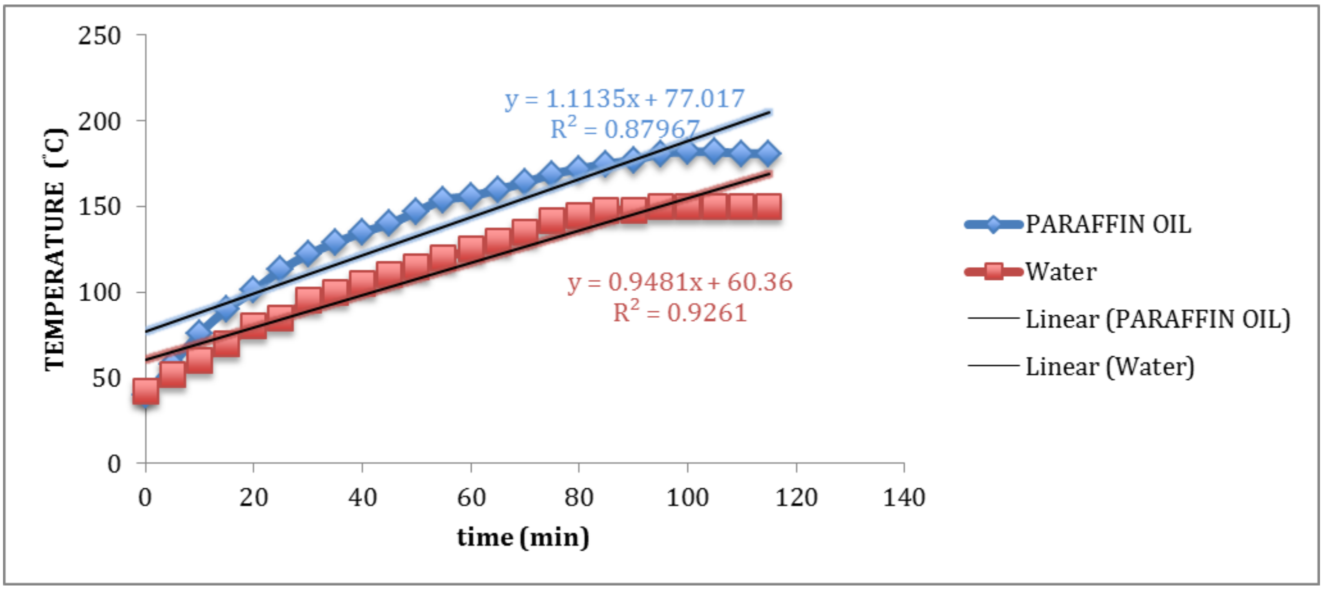

Fig 11: Temperature profile of Paraffin oil vs Water

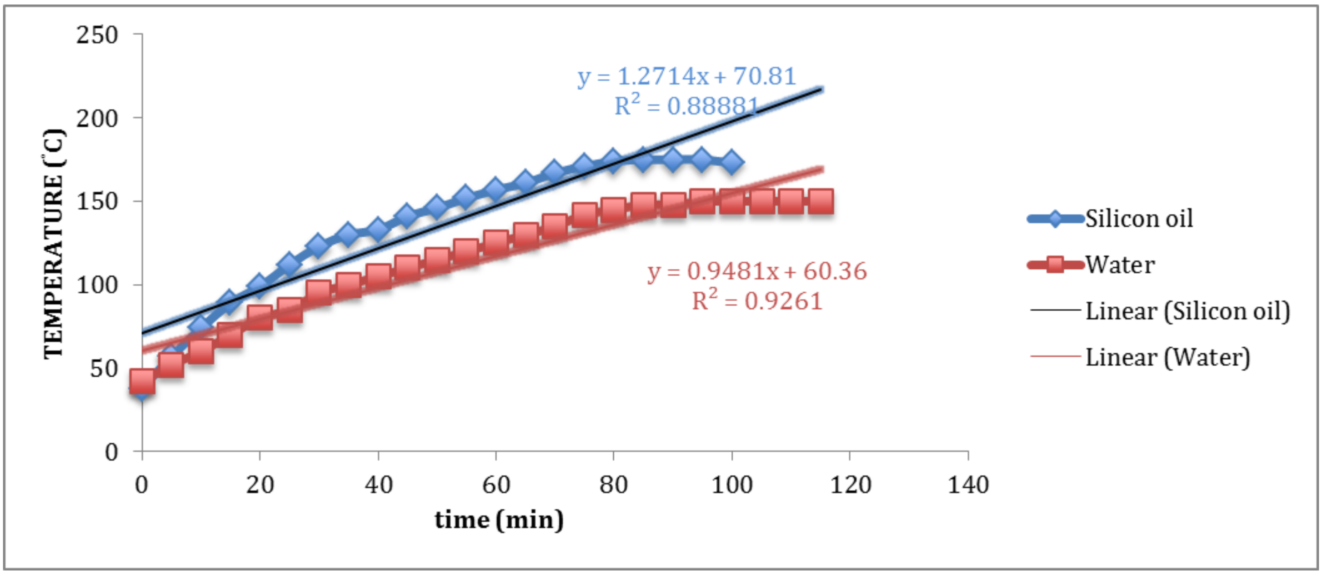

Fig 12: Temperature profile of Silicon oil vs Water

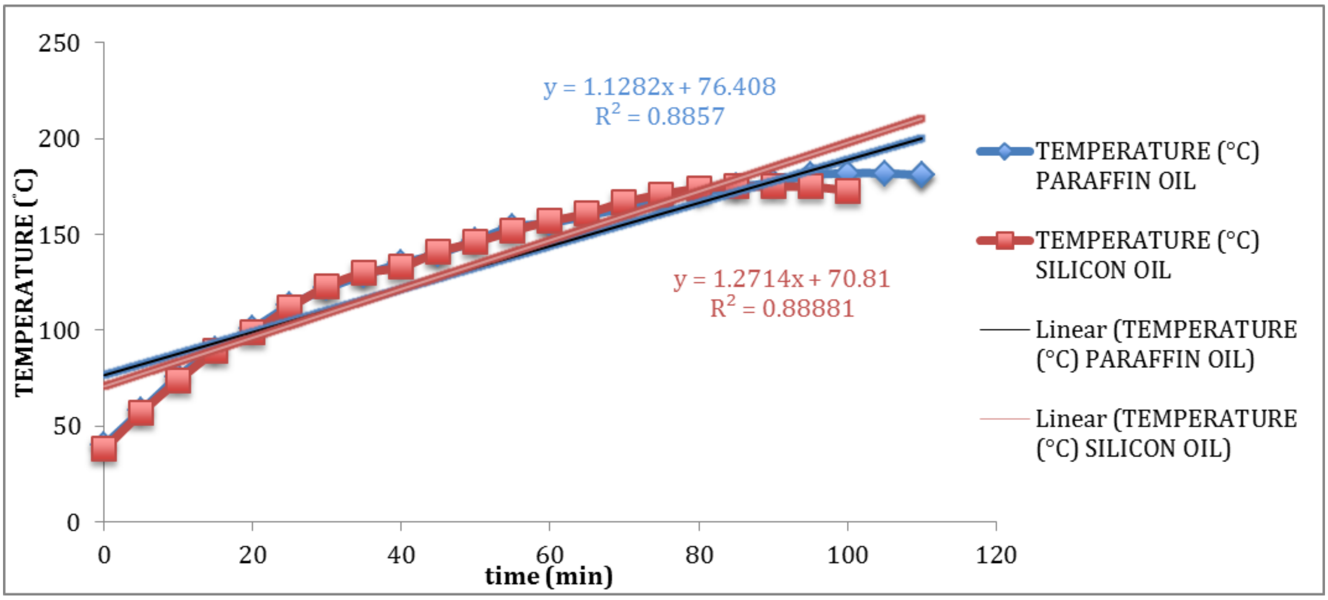

Fig 13: Temperature profile of Paraffin oil vs Silicon oil

Conclusions

In present study, it was found that phase changing salts has major problem of crystallization when they get cooled after heating which also results in difficulty in reheating and storage. The phase changing salt acetamide produced toxic fumes which may cause breathing problems and can harm the liver. Paraffin oil and silicon oil were found suitable heat transfer materials for milk processing as per the required temperature range. Developed solar parabolic concentrator based pressure vessel was able to heat the fluids to sufficient temperature required for most of the dairy and food processing operations. Thermic oils allow low pressure heating in very high degrees of temperature whereas the water created a maximum pressure of 4 kg/cm^2. Among the selected two thermic oils, paraffin oil gives higher degrees of temperature.

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