

# **An experimental investigation on the effect of ferrofluids on the efficiency of novel parabolic trough solar collector under laminar flow conditions**

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## **Abstract:**

The paper is related to the use of magnetic nanofluids (ferrofluids) in a direct absorption solar parabolic trough collectors enhances thermal efficiency compared to conventional solar collectors. By applying the right magnetic intensity and magnetic field direction, the thermal conductivity of the fluid increased higher than typical nanofluids. Moreover, the ferrofluids exhibit excellent optical properties. The external magnetic source is installed to alter the thermos-physical properties of the fluid, and the absorber tube does not have selective surface allowing ferrofluids to absorb the incoming solar irradiance directly. In this paper, an experimental investigation of the performance of direct absorption solar collector using ferrofluids as an absorber. Various nanoparticle concentrations 0% to 1vol% at the operational temperatures between 19°C and 40°C were used in the current study. The results show that using ferrofluids as a heat transfer fluid increases the efficiency of solar collectors. In the presence of the external magnetic field, the solar collector efficiency increases to the maximum, 25% higher than the conventional parabolic trough. At higher temperatures, the ferrofluids show much better efficiency than conventional heat transfer fluid. The study indicated that nanofluids, even of low-content, have good absorption of solar radiation, and can improve the outlet temperatures and system efficiencies.

**Keywords:** solar energy, parabolic trough, ferrofluids

## **1. Introduction**

The demand for modern energy services is increasing rapidly. Solar energy has the potential to meet a significant portion of the world's energy demand. Solar energy is one of the cleanest renewable forms with little or no impact on the environment. Concentrated Solar Power (CSP) is one of the methods to harvest sun's energy. CSP systems have the advantage of easier energy storage compared to photovoltaic (PV) systems. Several CSP technologies have been studied and evolved, and others have been successfully used commercially. CSP technologies include the parabolic trough systems, parabolic dish systems, solar tower systems and linear Fresnel systems [1].

The most commercially and technically developed CSP technology is the parabolic trough technology. Parabolic trough is not only effective in power generation but also useful for industrial process heat application. The temperature ranges for industrial process heat applications are between 70°C and 250°C [2,3]. A comprehensive review about Parabolic trough collector was published recently [4]. The successful operation of the first solar electricity generation system (SEGS) in California's Mojave Desert was the reason for the technical and commercial success of parabolic trough systems. However, the cost of energy generated by CSP systems is higher than conventional energy sources. Several research and development initiatives have the goal to reduce the cost of energy from these systems by roughly 75% to become competitive with conventional energy in the future [5,6]. Many researchers work on improving the performance of CSP systems and make them cost competitive.

One of the methods to reduce cost is increasing the heat transfer performance of parabolic trough systems. Increasing the heat transfer performance will decrease the absorber surface temperature and subsequently reduce the receiver thermal loss particularly at the high operation temperatures [7,8]. This could be achieved by enhancing the convective heat transfer in the absorber tube.

Researchers have tried modifying the surface and the design of the absorber tube to enhance the convective heat transfer [9-13]. Others have used a different kind of heat transfer fluids such as molten salt or nanofluids to improve the performance of heat transfer [14].

In recent years, many researchers have investigated the effects of nanofluids on the enhancement of heat transfer in thermal engineering devices, both theoretically and experimentally. Nanofluids are a mixture of Nano-sized particles (1-100 nm) in a conventional heat transfer mediums. Heat transfer can be enhanced by increasing the thermal properties of heat transfer fluid (nanofluids). Nanofluids illustrating excellent thermo-physical properties are appropriate to enhance the efficiency of any thermal management systems by selecting base fluids with suitable nanoparticle materials, dispersion agents, nanoparticle sizes, and particle volume fraction [15,16].

Harvesting the solar energy using nanofluids has been the focus of few researchers. An overall review of the performance of solar collector using nanofluids was presented [17]. There are two methods to harvest the solar energy when nanofluids are used, which are direct absorber collectors and non-direct absorber collectors. Non-direct absorber collectors are the conventional solar collector with an absorber that has a selective surface to absorb the solar radiation. Direct solar collectors use a transparent receiver to allow nanofluids to absorb the solar radiation. Nanofluids show very good optical properties to absorb the solar radiation. In a fluid depth of 10 mm, 90% of the solar radiation was absorbed by nanofluids with 0.1% volume fraction [18].

A nanofluids-based concentrating solar system with direct absorber was numerically compared with a conventional one [19]. The results show that the use of nanofluids in the receiver can improve the efficiency by 10%. They also concluded that for 10–100 MWe power plants, using graphite/therminol VP-1 nanofluids with volume fractions approximately to 0.001% or less could be beneficial. A numerical study using FLUENT was developed to investigate the heat transfer

performance of Al<sub>2</sub>O<sub>3</sub>/ synthetic oil nanofluids in a trough collector tube with a non-uniform heat flux. Various nanoparticle concentrations and operation temperature were used in the study [20]. Three-dimensional Navier-Stokes mass, momentum, and energy equations were solved. The study used an LS-2 parabolic trough collector module, tested in the AZTRAK rotating test platform at SNL by Dudley et al. The heat transfer coefficient is increased as the concentration of the nanoparticles in the base fluid is increased. The heat transfer coefficient decreases with increasing operation temperature. Recently, a thermodynamic analysis using the entropy generation minimization method for a parabolic trough receiver tube was carried on. A synthetic oil-Al<sub>2</sub>O<sub>3</sub> nanofluid was used as heat transfer medium. The results show an improvement in thermal efficiency up to 7.6%. A maximum Reynolds number was obtained for which the entropy generation in the absorber is at a minimum [21].

A unique type of nanofluids is ferrofluids. Ferrofluids content ferromagnetic nanoparticles that exhibit higher thermos-physical properties compared to the conventional nanofluids. By applying the right magnetic intensity and magnetic field direction, the thermal conductivity of the fluid enhanced more than typical nanofluids [22]. The thermal conductivity enhanced by 300% when ferrofluids with 6% volume fraction were exposed to external magnetic field [23]. The aim of this work is to modify parabolic trough collector to increase the heat transfer performance by using ferrofluids. In particular, a modified parabolic trough collector using water Fe<sub>3</sub>O<sub>4</sub> nanofluids was built, and its efficiency was measured under the different working condition, according to BS EN ISO 9806:2013. The comparison between the heat transfer fluids has been performed in controlled and standard conditions, reducing the possibility of error.

## **2. Ferrofluids preparation**

The magnetite nanoparticles  $\text{Fe}_3\text{O}_4$  were prepared using co-precipitation methods. The average diameter of nanoparticles was 10nm. The surface of the nanoparticle was coated by Sodium dodecyl SDS, and suspended in water. SDS increase the stability of the suspension and avoid sedimentation of particles. Using a static position method, the stability of ferrofluids was investigated. The ferrofluids were left standing in a container for four months. The distance or color difference in sedimentation within ferrofluids was observed by naked eye. The change of concentration is barely noticed. SDS produced a lot of bubbles when used in the solar collector. Therefore, a defoamer (DF, Antifoam B Silicone Emulsion) was added to suppress the bubble formation. Rh DF concentration was 15% of the weight of the added SDS. The test of ferrofluids with and without defoamer is presented.

### **3. Experimental Setup**

The parabolic trough collector (PTC) used in the experiment consisted of a sheet of the reflective mirror with a parabolic shape, absorber tube, and electromagnets as shown in Fig.1. The reflective mirror was 1 mm thick high impact polystyrene sheet with white painting on the back. The reflectivity of the mirror is not considered in this study. At the focal line of the concentrator, an absorber tube was placed. The absorber used was a borosilicate glass tube to allow ferrofluids to absorb the solar radiation. No envelope was utilized in this experiment. Three electromagnets are placed in the entrance, middle, and the outlet of the absorber. The electromagnet is air core solenoid with an inner diameter close to the outer diameter of the absorber tube, allowing the absorber tube to enter into the electromagnet. The electromagnet generates a uniform magnetic field when a current is passing through the coils. Adjustable DC power supply is used to control the current applied to the electromagnet with maximum current of 5A. A solar light simulator of high flux irradiation was developed. Some experimental tests were carried out for various distances

of the light surface from the simulator surface to investigate the unevenness of variations in light distribution. A pyranometer was used to study the solar radiation. The maximum unevenness error percentage was about 12.3%, which is in a good agreement within the permissible limits of 15% provided by British standards for testing a solar simulator. The solar simulator turned on and kept for 30 minutes before taking any readings.

An experimental setup was developed based on BS EN ISO 9806:2013 to study the performance of the proposed ferrofluids parabolic trough. Fig.2 shows the schematic of the experimental setup. The experimental set up consisted of the water tank, pipeline system, water pump, parabolic trough, heat exchanger, chiller, chiller pump, and measurement system. A solenoid valve was used to adjust the flow of ferrofluids. Flow rate is measured by an ultrasonic flow meter, FLOWNETIX 100. The temperatures in the inlet, outlet and atmosphere were measured by non-magnetic type T thermocouples. The pressure was measured by a pressure transducer, PTX 14 DRUCK. The chiller used was water chiller, Hailea HC series chiller.

A steady –state method was used to calculate the parabolic trough efficiency, according to BS EN ISO 9806:2013 standard. The test condition is shown in Table 1.

The usable heat extracted by the parabolic trough,  $\dot{Q}_U$ , is calculated by Eq. (1)

$$\dot{Q}_U = \dot{m}_f C_{p,f} (T_{out} - T_{in}) \quad (1)$$

Where  $\dot{m}_f$  is the mass flow of ferrofluids  $C_{p,f}$  is the specific heat capacity of ferrofluids which is calculated by Eq.2

$$C_{p,f} = (1 - \varphi) C_{p,w} + \varphi C_{p,np} \quad (2)$$

Where  $C_{p,w}$  and  $C_{p,np}$  are specific heat capacity of water and nanoparticles, respectively. The heat capacity is effected by the temperature. Therefore, the heat capacity calculated at the mean temperature  $T_m$  which calculated by Eq.3

$$T_m = \frac{T_{in} + T_{out}}{2} \quad (3)$$

The thermal efficiency can be calculated by Eq. 4

$$\eta = \frac{\dot{Q}_U}{I_D A_C} \quad (4)$$

Where  $\eta$  is the efficiency of the parabolic trough,  $I_D$  is the direct solar radiation and  $A_C$  is the area of the collector.

The solar radiation uncertainty is less than 2%. The uncertainty of mass flow is less than 1%. Uncertainties for inlet and outlet temperatures were less than 0.1 °C. Complex uncertainty was calculated by Eq. 5 and was between 1% and 5.2%

$$U_\eta = \sqrt{\left(\frac{\partial \eta}{\partial \dot{m}_f} U_{\dot{m}_f}\right)^2 + \left(\frac{\partial \eta}{\partial I_D} U_{I_D}\right)^2 + \left(\frac{\partial \eta}{\partial T_{out}} U_{T_{out}}\right)^2 + \left(\frac{\partial \eta}{\partial T_{in}} U_{T_{in}}\right)^2} \quad (5)$$

Table 1 Parameters of the parabolic trough and test condition

Parameters	Values
Length of the receiver	500 mm
Width of the aperture	250 mm
outer Diameter of the absorber	15 mm
Solar irradiance	1000 W/m <sup>2</sup>
Mass flow	0.02 kg/s
Magnetic field intensity	3.14 6.28 ,10.47mT

#### 4. Result and discussion

The efficiency of the parabolic trough was investigated with distilled water-Fe<sub>3</sub>O<sub>4</sub> ferrofluid at a concentration of 0% and 0.05Vol%, and a magnetic field intensity of 0 and 10.5 mT. The magnetic field intensity was similar to a study on the thermal conductivity of the ferrofluids [24]. The mass flow rate was close to those used in previous studies on solar collector using nanofluids [25,26]. Thermal efficiency analysis of parabolic trough, with water and ferrofluids, was carried out by increasing the difference between the mean temperature  $T_m$  and the temperature of the atmosphere.

The test started by turning on the sun simulator, the ferrofluids pump, and the chiller pump. The sun simulator needs 30 minutes to reach the maximum intensity and remain constant. The chiller was used to assure a constant inlet temperature in the time of measurements. Then the chiller was adjusted to increase the inlet temperature. Fig. 3 shows the efficiency of parabolic trough for both water and Fe<sub>3</sub>O<sub>4</sub>-water ferrofluids 0.05% with no magnetic field applied under laminar flow condition. By using the water, the highest efficiency value 10% was obtained. At a  $T_m$  0.1 °C m<sup>2</sup>/W The lowest efficiency value has been obtained, 0%. In this case inlet temperature, ambient temperatures were 30.04°C and 20.23°C respectively.

By using ferrofluids, 0.05% as heat transfer fluid with no external magnetic field applied the highest efficiency of 16% was obtained. The lowest efficiency value has been obtained, 6%. In this case inlet temperature, ambient temperatures were 30.04°C and 20.23°C respectively. When the difference between the mean temperature and the ambient temperature increase to 6 °C, Fe<sub>3</sub>O<sub>4</sub>-water ferrofluids 0.05% shows much higher enhancement compared to water, around 16% higher. Fig4 shows the result of Fe<sub>3</sub>O<sub>4</sub>-water ferrofluids 0.05% with applied magnetic field. The efficiency increases with increasing the magnetic field intensity when the orientation of the magnetic field is parallel to the direction of the flow. The maximum efficiencies of 30%, 35%, and 40% for 3.14mT, 6.28mT, and 10.47mT respectively. Water was also used with external magnetic field. There is no effect of magnetic field on the measurements.

Nanoparticles enhance the thermophysical properties of the fluid which allow the heat to transfer faster from the absorber surface to the fluid. Many mechanisms are put forward to account the enhancement in the thermo-physical properties of ferrofluids, which are ballistic phonon transport, Brownian motion induced micro-convection and the aggregation of nanoparticles. Systematic studies reveal that the conduction path through agglomerates is one of the most significant factors



responsible for the dramatic enhancement [24,27]. The magnetic field induced the chain-like structure of nanoparticles of magnetite in magnetic nanofluids which allow heat to transfer faster through the fluid. When the magnetic field was increased the chain length increased, creating more bridge of thermal energy conduction along the magnetic field direction. Moreover, ferrofluids show enhancement in optical properties (absorption and scattering) compared to base fluids. The enhancement is a function of nanoparticles size, concentration and the optical path length [18,28]. For all these reasons thermal efficiency of solar collector increases by using ferrofluids. Increasing the magnetic field further will not affect the thermal efficiency because the particles reached to a saturation magnetization.

## **5. Conclusion**

An innovative direct absorption parabolic trough collector, uses ferrofluids as heat transfer fluid and absorber, was built. An experimental comparison of thermal efficiency between two heat transfer fluids  $\text{Fe}_3\text{O}_4$ -water ferrofluids with 0.05% and distilled water, working in the same parabolic trough, has been performed. This parabolic trough benefits from the magnetic and optical property of ferrofluids which enhance the thermal efficiency of the collector. The results show that using ferrofluids as a heat transfer fluid increases the efficiency of solar collectors. The thermal efficiency rose 16 % maximum when ferrofluids were used without external magnetic field compared to base fluid. In the presence of the external magnetic field, the solar collector efficiency increases to the maximum, 40% higher than the conventional parabolic trough. At higher temperatures, the ferrofluids show much better efficiency than conventional heat transfer fluid. The ferrofluids show better heat transfer coefficient and decrease the surface temperature of the absorber. The modification of the new parabolic trough consists of adding an electromagnetics to the absorber tube because the external magnetic field would enhance the thermo-physical

properties of the ferrofluids. Efficiency was calculated at various reduced temperature difference. Ferrofluids are more efficient at high operation temperatures.

## 6. Reference

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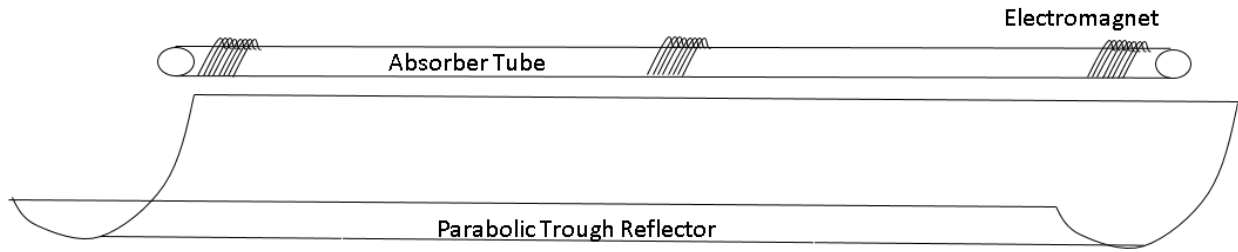


Figure 1 Schematic of proposed parabolic trough Collector

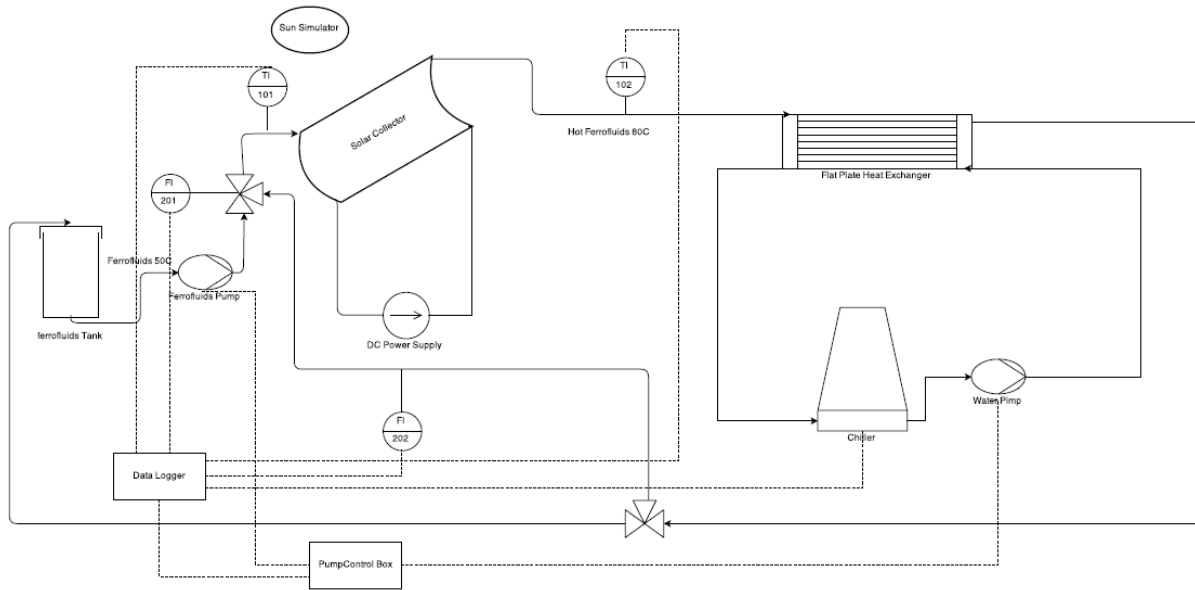


Figure 2 Schematic and photograph of the experimental setup

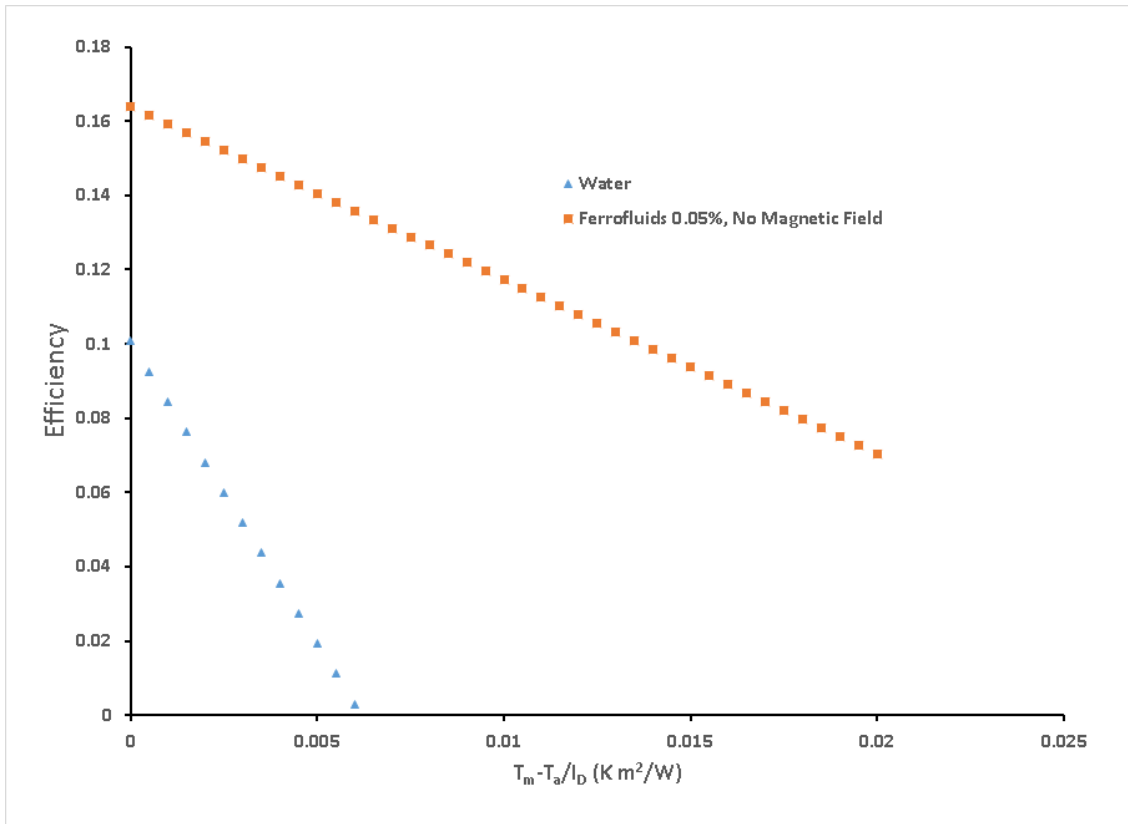


Figure 3: Thermal Efficiency of the parabolic trough with Water and Ferrofluids without Applied external magnetic field in the laminar region.

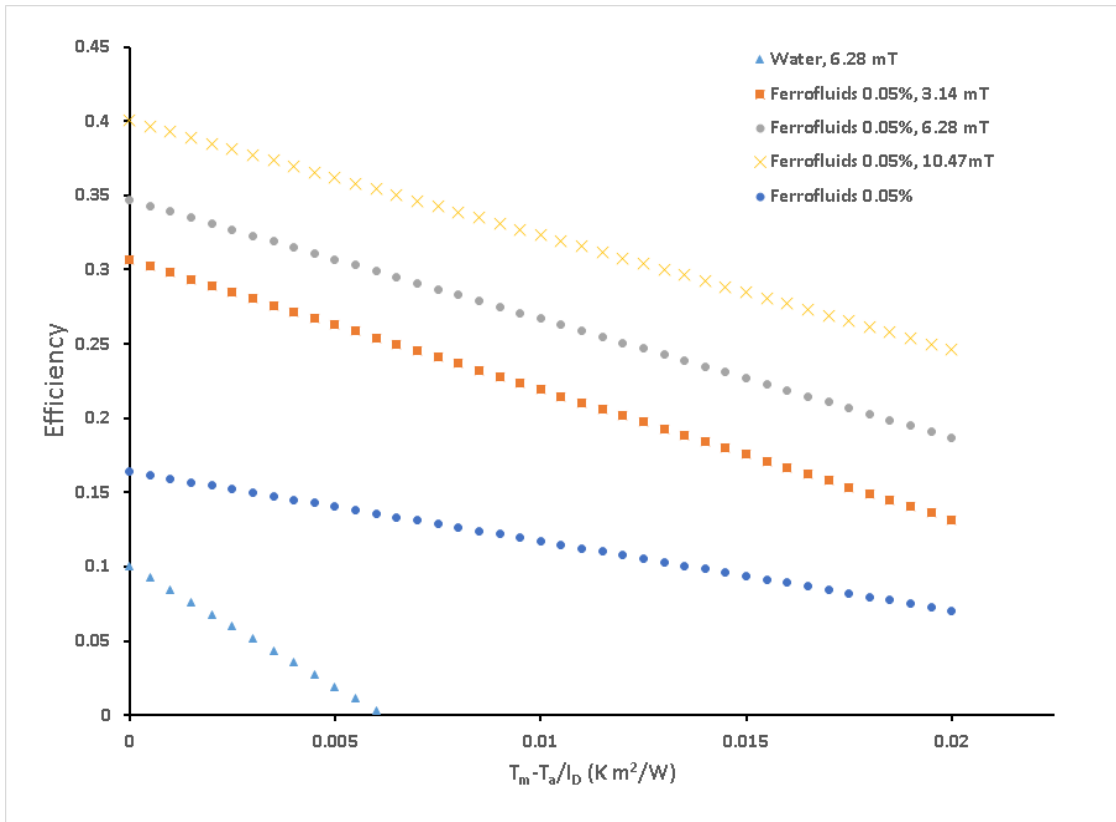


Figure 4 Thermal Efficiency of the parabolic trough with Water and Ferrofluids in the presence of an external magnetic field in the laminar region.