Chapter 1: Introduction

1.1 Background and Motivation

Freely available solar energy can be utilized for process heating applications, especially for mitigating the use of fossil fuels and the emission of greenhouse gases. For instance, solar thermal systems comprise a receiver or collector, thermal energy storage, and if needed, a power block [1][2][3][4]. A receiver or collector is a specially-designed heat exchanger, that is exposed to solar irradiance, and a heat transfer fluid is used to recover the generated heat via forced convection. Based on the application of temperature range, the solar thermal system is divided into low (< 353 K), medium (353-573 K), and high temperature (beyond 573 K) solar thermal systems [4][5]. A low-temperature solar thermal system, like a flat plate collector, is widely used for space heating/cooling and water heating, whereas the high temperature concentrated solar thermal (CST) systems are widely used for power generation. Interestingly, despite many industrial and domestic applications, medium-temperature CST systems are less explored than low or high-temperature systems. The applications for the medium-temperature range include milk processing (373 – 453 K), soap manufacturing (473-533 K), synthetic rubber preparation (423-473 K), bleaching (403-423 K), and pre-processing for plastic (393-413 K) [4][5]. Recently, an evacuated-tube flat-plate collector and a parabolic trough collector with thermal oil are being explored, as an option, for power generation with an organic Rankine cycle (ORC) [6][7]. The concentrating parabolic trough collector is preferred for power generation using (a) thermal oil for a temperature up to 773 K and (b) molten salts for a temperature up to 823 K. Some of the solar thermal systems and their operating conditions are summarized in Table 1.1.

Table 1.1 Solar thermal systems, applications, and their operating conditions.

Solar Thermal System	Heat Transfer Fluid
Application: process heating using, e.g. a flat-plate collector [5]	Water
Application: heating, cooling, and power generation using, e.g. a parabolic trough collector [8]	Pressurized water, ThermінolVP1, molten salt, liquid Sodium, air, CO_2, and He.
Application: heating, cooling, and power generation using, e.g. ORC (U-shaped evacuated-tube collector) and/or a parabolic trough collector [6][7]	Therminol66
Application: heating using, e.g., a parabolic trough collector [9]	Nanofluid, Hybrid-nanofluid Al_2O_3-TiO_2-syltherm-oil

A solar thermal system is designed for the medium-temperature range (373-573 K) to augment these investigations and is illustrated in Figure 1. This depicts a collector that focuses solar irradiance onto a tubular receiver. A heat transfer fluid flows through the receiver's absorber tube and extracts the generated heat. The resulting hot fluid is transported to thermal energy storage, and the relatively cold fluid is circulated through the field. The system is envisaged for the series/parallel operation of heating and cooling applications. A brief overview of the parabolic trough absorber and heat transfer fluids, including nanofluids, is presented.

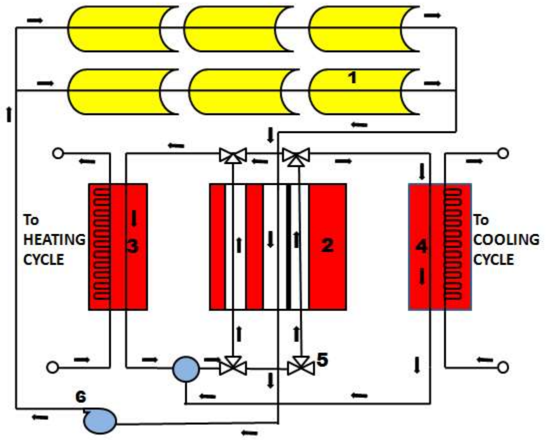

Figure 1.1 A schematic of the solar-based heating and cooling system: 1: Solar collector with a receiver, 2: Thermal energy storage, 3 & 4: Heat exchangers, 5: Valve, and 6: Pump.

A parabolic trough collector, generally, comprises parabolic-shaped primary (and secondary) reflectors, a long tubular receiver including an absorber and glass cover, a foundation or a metallic framework, a tracking mechanism, and a transmission system. A heat transfer fluid, flowing inside an absorber, is used for transporting the concentrated irradiance-based generated heat from an absorber and transporting the same to a storage or an application. Figure 1.2a presents the solar energy diagram and its distribution in the PTC using a secondary reflector [10]. A typical flux distribution on the outer peripheral surface of a parabolic trough absorber is shown in figure 1.2b (shown by the original LS-2 PTC). This shows a non-uniform distribution of heat flux on the outer peripheral surface of an absorber. The lower half of the parabolic trough absorber is exposed to a high flux concentration exceeding 40 Suns (40 kW/m^2), and the upper half of the absorber tube, without a secondary reflector, is exposed to a much lower heat flux, say 1 Sun at the most, leading to a high heat flux ratio between the lower and upper half of the absorber. Interestingly, the use of a secondary reflector that focuses a part of the reflected direct solar irradiance from the primary parabolic-shaped reflector onto the upper half of the absorber.

This leads to, as expected, a lesser flux non-uniformity on the absorber periphery compared to the case without a secondary reflector (see figure 1.2a).

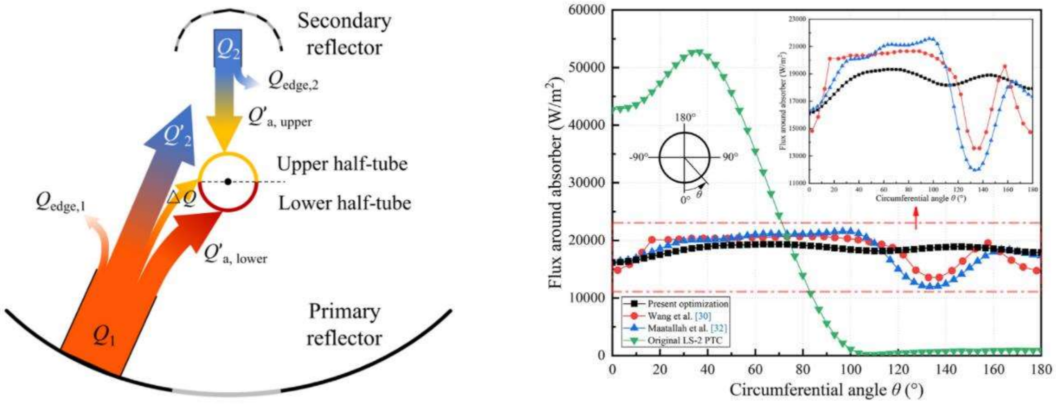

Figure 1.2 a) Solar energy flow diagram and distribution in the Parabolic Trough Collector –Secondary Reflector (PTC-SR) [10] b)Comparison of circumferential flux distribution on absorber surface for different secondary reflector designs for PTC [10].

As explained, heat transfer fluids (HTFs) are necessary to recover, transport, and store heat in a thermal system. The heat transfer fluids like thermal oil (TherminolVP1 and Therminol66), molten salts (e.g., solar salt, Hitec, and Hitec XL), and liquid metals (e.g., sodium and lead-bismuth eutectic) are preferred for parabolic trough collector-based CST system [1][2]. However, commonly available fluids like vegetable oil are being explored, as possible alternatives, for applications in the medium-temperature range[11][12][13][14]. A recent investigation has indicated a promising future for such less exotic fluids that can sustain up to 473 K and are thermally stable for up to 2160 cycles [15]. Nanofluids and hybrid nanofluids are engineered colloidal, having nanometer-sized particles dispersed in a base or pure fluid, and are increasingly considered potential HTFs, thanks to their synergistic effect of thermophysical properties. A nanofluid with two or more uniformly dispersed nanoparticles is *usually* called a *hybrid* nanofluid, otherwise termed *mono-*

dispersed or *simply* a nanofluid. It is worthwhile to note that the selection of a nanoparticle for a given base fluid is essential, considering the enhancement of favorable thermophysical properties of the nanofluids. This thesis uses the term parabolic trough absorber or absorber for parabolic trough collector or PTC absorber interchangeably. A detailed literature review in chapter 2 of the thesis revealed several research gaps to be addressed before adopting the nanofluids as HTFs in an absorber for parabolic trough collector-based systems. This leads to the framing of the following objectives and novelties of the present thesis:

1.2 Objectives and Novelty of the Thesis

- The development of a selection criterion for heat transfer fluid is required for removing and transporting heat from a PTC absorber.
- Deduction of generalized Nusselt number correlations for turbulent heat transfer with mono-dispersed- and hybrid– nanofluids in a PTC absorber
- Investigation of the effect of discrete heating conditions on the heat transfer in PTC absorber.
- Adaptation of the generalized Nusselt number correlations for heat transfer in a PTC absorber subject to discrete heating.
- Experiments are performed with nano-oils to assess the applicability and limitations of generalized Nusselt number correlations.

The novelty of the thesis is the deduction of generalized Nusselt number correlations for the turbulent flow of nanofluids and hybrid nanofluids aimed at the relatively unexplored medium-temperature solar thermal systems. Also, the correlations are adopted for discrete heating conditions relevant to solar thermal systems.

1.3 Thesis Structure

There are **seven chapters** in the thesis. A parabolic trough absorber, heat transfer fluid, Nusselt number correlations, objectives, and the novelty of the thesis are covered in the **first chapter**, which also discusses background and motivation. The **second chapter** includes a review of the literature on heat transfer fluid, Nusselt number correlations for nanofluid and hybrid nanofluid, effects of discrete heating, and the identified research gaps. The generalized Nusselt Number correlation for nanofluid is determined in the **third chapter**, which also develops a selection criterion for heat transfer fluids. The deduction of generalized Nusselt number correlation for hybrid nanofluids using a separation approach is covered in the **fourth chapter**. The purpose of the **fifth chapter** is to analyze the impact of discrete heating on a straight, long, smooth tube for the turbulent flow of nano-oil. The experiment with hybrid nano-oil in the **sixth chapter** was centered on determining the applicability and constraints of the generalized Nusselt number correlation. The conclusion and future scope are covered in the **seventh chapter** as well.