Chapter 1: Introduction

There is a growing scarcity of potable water due to the depleting reserves of fresh water and deterioration in quality of the naturally occurring water reserves [1-3]. This is leading to a looming water crisis which necessitates exploring alternative sources of potable water for the future. About 96.5% of all the water on earth is seawater. Of the remaining 3.5% only about 1% is in the form of freshwater lakes, rivers and ground water with the rest being frozen water in the form of polar ice caps, glaciers, ice and snow. The shear abundance of seawater when compared to freshwater makes it rewarding to explore the possibilities of using it as a source of potable water. Seawater desalination is especially useful in coastal areas as there is no additional cost of transportation involved. Reverse osmosis has been extensively used for desalination in many countries across the world [4-7]. Other methods such as membrane distillation, electro-dialysis, and solar stills are also being explored for desalination including some methods in which renewable energy like solar, wind, wave and geothermal energy are being employed [8-9]. Solar thermal energy can be used as the source for energy for many of the desalination methods and can result in lower costs [9]. The cost for desalination depends on the type of feed water, the desalination method used and the type of energy used [10]. Developing a desalination method that meets the need of potable water at the lowest cost, has low energy requirements and is preferably powered by a renewable source of energy is critical.

Membrane distillation is a promising process which could be extensively used for desalination in the future [11-16]. Membrane distillation can be used with brackish water and water containing other impurities. The main advantage of membrane distillation over reverse osmosis is that modules based on membrane distillation are resistant to fouling [17-18]. Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweeping Gas Membrane Distillation (SGMD) and Vacuum Membrane Distillation (VMD) are the configurations which are used in membrane distillation. In DCMD, the hot feed solution is in direct contact with a membrane which is in direct contact with the cold solution. A sweeping gas which is usually inert is used to sweep the vapor which is on the permeate side of the membrane in SGMD. In VMD, a vacuum is created on the permeate side of the membrane to direct the vapor out of the module for condensation. AGMD is a membrane distillation configuration in which the feed solution is in direct contact with the membrane and there is an air gap separating the membrane and the condensing surface. The air gap between the membrane and the condensing surface leads to a decrease in heat loss due to conduction [19-20]. However, there is an additional resistance to mass transfer due to the air gap which is a disadvantage associated with this process. It has been shown in the past that AGMD is the most energy efficient of all membrane distillation configurations [20-23].

The energy associated with pumping the hot saline feed water and the cooling fluid forms a substantial part of the energy requirements for AGMD process. Hence, using an air-cooled system instead of using the conventional water-cooled configuration may lead to a system with lower energy requirements which will in turn lead to lower running costs and has been studied as a part of present work. The condensing plate can be placed in such a way that it faces the windward side which will lead to cooling through buoyancy-induced convection. There have been studies in the past in which the internal temperatures of an AGMD module has been studied [24]. These studies have been used in this study when comparing an air-cooled system to the more conventional water-cooled one.

Employment of a superhydrophobic condensing surface has been shown to result in a substantial increase of permeate flux in past for the conventional AGMD configuration with a cooling channel [25-26]. This can be attributed to the fact that hydrophobic jumping droplet condensation has better heat transfer coefficients which results in faster condensation and an increased permeate flux [26-29]. Warsinger et al. [25] has conducted parametric study for a two channel AGMD system in which he studied the effect conductivity and hydrophobicity of support mesh, hydrophobicity of the condensing surface and air gap. Using the modules in series configuration can lead to greater yields as there is recovery of latent heat of permeate and the energy associated with the saline flowing out of one module is utilized in the next module.

With the objective of reducing the costs associated with desalination, air-cooled AGMD modules which have been assembled in series configuration are being studied in this paper. A parametric study in which the effect of air gap and hydrophobicity and conductivity of the support mesh for an air-cooled single channel system is being conducted as part of this study. The effect of having a hydrophobic condensing surface on the permeate flux is also being studied for the air-cooled module and in the case when the modules have been placed in series configuration.

The second part of the thesis is motivated by the objective of making the desalination process fully sustainable by using solar energy concentration systems to meet the thermal needs of a desalination system.

Solar energy harvesting can be done by either optically concentrating the energy or by using photovoltaic cells to convert the solar energy into electrical energy. In concentrated solar thermal (CST) systems, light collecting elements which are basically large mirror surfaces to focus sunlight on a smaller area is used. It can be used for applications such as power generation, thermal desalination, etc. Currently, in utility scale CST power plants parabolic troughs or flat mirrors (heliostats) are used which track the sun diurnally to concentrate sunlight onto the receiver [30,31]. Concentrated Solar thermal systems which use solar tracking are effective, but they suffer from major drawbacks like tracking error caused by wind loading, tracking cost, and the high capital cost of the mirrors and support structure [30]. To achieve the tracking motion and to support the heavy mirrors or the troughs, support structure and pylon, drive systems, and wiring are needed which account for almost 30–40% of the total cost [31]. Active tracking requires the heliostats or troughs to move. This movement needs them to be spaced apart to limit shading losses, thus leading to poor land-use efficiency [30-33]. The drawback with implementing wide spread use to solar energy is the high costs associated with it. To achieve competitive costs, solutions which eliminate the need for active tracking of the sum are required [30,34].

Optical waveguide based approach which utilizes total internal reflection (TIR) to concentrate sunlight on a smaller area is a promising approach. Planar waveguide solar concentrators are being explored in the area of photovoltaic based solar energy harvesting systems to focus solar irradiation on to the small area of solar cells [35-45]. Concentrated solar thermal systems based on total internal reflection can be based on either of the following two approaches: (a) luminescent solar concentrators (LSC) and (b) micro-optics solar concentrators with coupling features, which is the focus of this study. LSC consists of a waveguide dispersed with luminescent molecules (such as organic dyes, quantum dots, etc.) that absorb the incident light and re-emit at longer wavelengths. Some of the re-emitted radiation undergoes total internal reflection and is guided towards the receiver [41-45]. In a TIR based micro-optics solar concentrator, the incoming sunlight is focused by a lens array onto localized scatterers in the waveguide, which guides the light rays to the receivers by total internal reflection. Nonsequential ray tracing studies and laboratory proof-of-concept demonstrations of micro-optic concentrators fabricated for concentrating photovoltaics are being conducted [35-47]; this concept has not yet been applied to CST applications. Due to its lightweight nature the mounting and positioning of the waveguides does not require a lot of structural support, which in turn simplifies structural design and reduces cost. Since, there is no active tracking involved in this concept the overall cost of the system is low and the land-use efficiency is also better as there are no shading concerns [35]. It has been shown that these systems have the ability to focus the sunlight throughout the day with only a few centimeters of lateral movement [46,47]. This leads to considerable reduction in the tracking cost. Fixed axis concentrators which have no tracking mechanism can be used as seasonal concentrators [48], especially for lower temperature applications. Self-tracking planar concentrators based on thermal phase change actuator [49] and light induced refractive index change [50], that can achieve high levels of concentration over a wide acceptance angle (> 40 degrees) are also being explored.

TIR based optical waveguides have been explored for concentrated photovoltaics applications [35-50] but there have been very few investigations of the concept for concentrated solar thermal applications. The numerical efforts of in this field have been mostly limited to optical analysis based on ray trace modeling [35-37,39,48,49], with a few exceptions of recent experimental effort in analyzing the temperature distribution within a luminescent waveguide for photovoltaic applications [51]. However, to implement the TIR concept in CST applications an integrated optical and thermal analysis of the system is required. In this thesis, an analytical closed form solution for the coupled optical and thermal transport in a TIR based ideal planar waveguide concentrator integrated with central receiver is presented. In this study the possibility of using a radial waveguide which concentrates the light towards the centrally placed receiver instead of the conventional planar waveguide design which has the receiver at the ends of the waveguide has been explored. The radial design could lead to better geometric concentration ratio as the light rays are focused on a smaller surface and better collection efficiency as the rays travel for a shorter distance before they are collected at the receiver. The spatial distribution of temperature and the irradiation reaching the receiver has been obtained based on various design and operating parameters. The results guide us towards effective design of the system based on the considerations of thermal stress, wind loading, net thermal power delivered to the receiver, collection efficiency and aperture area requirement. A simple cost analysis is presented, and a new performance metric namely, levelized cost of power (LCOP) is introduced to provide useful insights into optimal waveguide concentrator-receiver configurations that yield the minimum levelized cost of power (LCOP) based on the tradeoff between cost and thermal power delivered to the receiver. This study also provides a feasible path forward towards meeting the cost and performance objectives for applications such as, thermal based desalination [52,53], and CST power generation.