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Mixed Convection Heat Transfer in an Absorber Tube with Non-uniform Heat Flux Distributions Boundary for a Linear Fresnel Solar Thermal Collector: Review Work

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Abstract

This work reviewed the mixed convective heat transfer in absorber tubes similar to that of a linear Fresnel solar collector. Studies on the experimental and numerical simulations on linear Fresnel solar thermal collectors were reviewed to establish the gaps in the literature for further studies that could improve the overall performance of a linear Fresnel solar collector. The solar heat flux impinges on the absorber tubes of a linear Fresnel solar collector, from underneath independent of the position of the sun. This resulted in a circumferential non-uniform heat flux distributions around the tube wall, contrary to previous studies which assumed uniform heat flux boundaries for convenience. A number of studies had investigated mixed convection heat transfer in horizontal circular tubes for uniform heat flux distribution boundary symmetrical to the direction of the gravitational field. Studies are lacking for linear Fresnel solar collectors due to non-uniform circumferential heating of the absorber tubes from underneath for weak turbulent or laminar flow conditions. Studies are also lacking in the literature for the case of asymmetrical non-uniform heat flux distributions boundary on the absorber tube when the incident solar radiation deviated from the zenith angle position due to the sun tracking system of the collector. The degree of asymmetry of the heat flux distribution boundary could have significant influence on the internal heat transfers characteristics of the absorber tubes.

Keywords: Linear Fresnel solar collector • Mixed convection heat transfer • Solar collector absorber tubes • Uniform and non-uniform heat flux

Introduction

The absorber tubes of solar thermal collectors are very critical in converting the radiant solar heat flux into thermal energy of the heat transfer fluid. Internal heat transfer coefficients of the absorber tubes are very essential in determining the heat transfer rate by convection from the inner wall boundary of the tube to heat transfer fluid inside the tube. The improved thermal efficiency of solar collectors system could be achieved with an increase in the fluid side internal heat transfer coefficient of an absorber tube [1]. The solar heat flux impinges on a horizontal absorber tube of a linear Fresnel solar collector, from underneath independent of the position of the sun. This results in a circumferential non-uniform heat flux distributions around the tube-wall and hence non-uniform heat transfer to the heat transfer fluid. Under the influence of gravitational field and the non-uniform circumferential heating of the absorber tubes, a mixed convection heat transfer scenario could occur where the influence of the induced buoyancy driven secondary flow component becomes comparable with the forced convection situation [2]. Depending on the flow regime and turbulence levels, and the heat flux distribution boundary type, the induced buoyancy driven flow could significantly influence the internal heat transfer characteristics of the absorber tube. This situation needs to be adequately investigated for a linear Fresnel solar collector absorber tube for weak turbulent or laminar flow operating conditions. The linear Fresnel solar collectors applications for weak turbulent or laminar regime operating conditions, could be applicable for industrial process heat for make-up water preheating and heat supply for a particular process, solar space cooling and large volume hot water system for institution such as hospital, hotels, schools etc [3].

This work gives a representation of a linear Fresnel solar collector system. It reviews the convective heat transfer in absorber tubes of a linear Fresnel solar collector system with symmetrical and asymmetrical non-uniform circumferential heat flux distribution boundaries in terms of direction of the gravitational field. Studies on the experimental and numerical simulations studies on linear Fresnel

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solar thermal collectors for non-uniform circumferential heat flux distribution boundaries are also reviewed to establish the gaps in the literature for further studies that could improve the overall performance of the system [4].

Literature Review

Linear Fresnel solar collector system

Figure 1 represents a linear Fresnel solar collector system indicating its components. The mirrors strips concentrate the solar radiation on a fixed receiver cavity mounted on a linear tower. The incident solar radiation, after reflection from the mirrors, impinges on the absorber placed along the length of the focal zone of the concentrator (Figure 2).

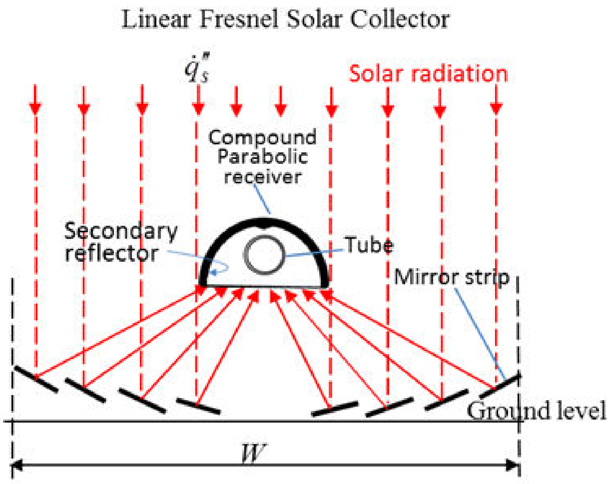

Figure 1. Linear Fresnel solar collector with a compound parabolic type receiver cavity.

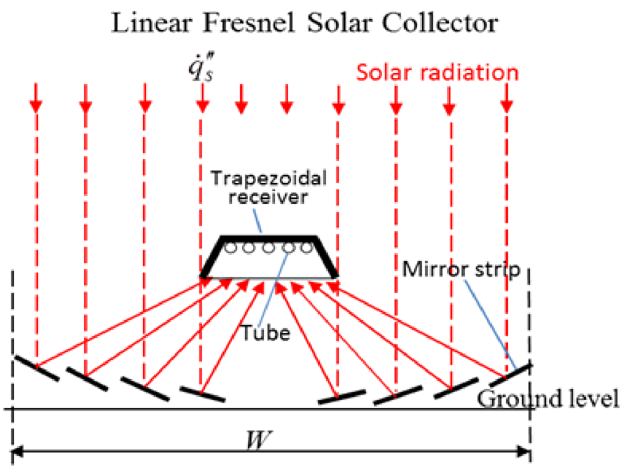

Figure 2. Linear Fresnel solar collector with a compound parabolic type receiver cavity.

The second stage concentrator enlarges the target for the Fresnel reflectors and also provides insulation to the absorber tube. Figure 2 is another linear Fresnel solar collector system with a trapezoidal receiver cavity type. The cavity has multiple absorber tubes with diameter smaller than that of the compound parabolic type, mounted inside the cavity and covered with a transparent glass. The back sides of the cavity are covered with insulator to reduce conduction heat loss and the front glass pane to reduce convective heat loss. The trapezoidal cavity is, however preferred to a compound parabolic type, which has a single large diameter absorber tube, due to difficulties in generating steam in a horizontal tube [5].

The earlier designs and development of linear Fresnel solar collectors were focused on a higher Reynolds number turbulent flow applications suitable for steam generation for power generation and for some industrial process uses. Studies are lacking in the literature for low turbulent or laminar flows heat transfer applications for linear Fresnel solar collectors that could explore the advantages of buoyancy induced secondary flow effects, which could enhance heat transfer rate far above pure forced convection cases or even in the transition regime with abrupt increase in the Nusselt number. Higher Reynolds numbers turbulent flow applications are usually associated with higher pumping energy and cost requirements due to very high pressure drop. On the other hand, low turbulent or laminar flow applications for linear Fresnel solar collector systems are very essential to be considered for reduced operation power and the thermo-economic (cycle temperature, energy harvested, pumping power, capital costs) performance for the collector at low turbulent or laminar flow are also needed in the literature [6-10].

Solar flux distributions on the absorber tubes of linear Fresnel collector

In a linear Fresnel solar collector, the irradiation heat flux impinges on a horizontal absorber tube from underneath independent of the position of the sun. As revealed by ray tracing design and simulation studies, this results in circumferential non-uniform heat flux distributions around the tube-wall. Figures 3 shows the representations of uniform and non-uniform heat flux distribution boundary on a horizontal absorber tube similar to that of a linear Fresnel solar collector [11-15].

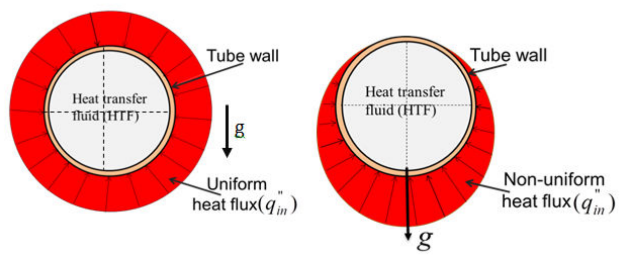

Figure 3. Uniform and non-uniform solar flux distributions boundary on a horizontal absorber tube similar to that of a linear Fresnel solar collector.

However, previous studies on linear Fresnel solar concentrating collector absorber tubes were generally based on the assumption of a uniform solar heat flux distributions boundary as shown in Figure 3. For instance, Dey described the basic design and thermal modeling for a linear absorber of an inverted receiver cavity for a north-south oriented compact linear Fresnel reflector. In this study a uniform solar flux was assumed and model equations were given for the absorber tube sizing and spacing, and the possible absorber design configurations. The experimental validation for an optical and thermal modeling of a linear Fresnel collector for a water heating system by assumed a uniform radiation flux impinging on the absorber tube [16-20].

Velazquez performed a numerical simulation of a linear Fresnel reflector concentrator to evaluate its technical feasibility as a direct generator in a Solar-GAX cycle with a cooling capacity of 10.6 kW. They also assumed a uniform irradiation flux impinging on the receiver and presented one-dimensional numerical models for the fluid flow inside the absorber tube, heat transfer in the tube-wall and the receiver cover, and thermal analysis for the concentrator. The assumption of uniform heat flux is, however, not usually correct as has been revealed in a number of optical design and simulation performance studies. The ray tracing simulation results by indicated that the radiation intensity is approximately evenly distributed on the lower part of a collector tube, but that it is very low in the upper part of the tube, indicating non-uniform radiation heat flux on the absorber tube. The optical design and performance studies by and also revealed that the heat flux distribution on the outer-wall surface of an absorber tube has a peak at the central portion from underneath and decreased rapidly on both sides of the tube. Also in the heat flux distribution was a maximum at the bottom of the outer surface of the absorber tube followed by the sides and then decreased to the top portion of the tube. Abbas conducted a steady state numerical simulation of the thermal performance of the linear Fresnel collector receiver tubes of the trapezoidal cavity to investigate the optimum tube diameter and length. They noted that the solar heat flux impinging on the receiver surface was far from being uniform, but for convenience they assumed a uniform radiation flux impinging on the receiver absorber tube [21].

Mixed convection heat transfer with symmetrical heat flux distributions boundary

Previous studies on the thermal performance of linear Fresnel solar concentrating collector absorber tubes were generally for convenience based on the assumption of a uniform solar heat flux distributions boundary. As already stated, the solar heat flux impinges on the absorber tube of a linear Fresnel solar collector from underneath independent of the position of the sun and results in circumferential non-uniform heat flux distributions around the tube-wall as shown in Figure 3. Extensive studies on the influence circumferential non-uniform heat flux distributions on the convective heat transfer for a linear Fresnel collector system absorber tube are lacking in the literature. Only study the considered non-uniform heat flux distributions for a linear Fresnel solar collector type absorber tube model for the turbulent flow regime of water where buoyancy driven secondary flow was weak in comparison with the forced-convection effects. The heat flux distribution boundary was based on sinusoidal function cases of the absorber tubes heated from below with a peak heat flux being present at the lowest region of the tube as in the case of Figure 3. Investigation needs to be extended for the laminar or weak turbulent flow regime for single phase liquid flow as would be applicable in, for instance, the pre-heating phases during direct steam generation, or in thermal storage systems that do not require phase change. This is very essential considering that in the laminar or weak turbulent flow regime, the heat transfer characteristics of the absorber could differ significantly from the case of pure forced convection due to buoyancy effects which usually distort the temperature and velocity profile of the pure force convection heat transfer processes [22-25].

A number of experimental and numerical studies have been conducted for mixed convection heat transfer in horizontal circular tubes similar to that of a linear focusing solar collector absorber tube. The influence of buoyancy driven secondary flow on the forced convective heat transfer processes for the case of circumferential non-uniform heating of an absorber tube in a laminar or weak turbulent flow regime is lacking in literature. Fand and Keswani noted that in all convective heat transfer processes, forced and natural convection coexist, since the density gradient and the associated buoyancy force field still exist. Ghajar and Tam also noted that the influence of buoyancy forces on the forced convection heat transfer in horizontal tubes is dependent on the Grashof, Prandtl and Reynolds numbers as well as the wall boundary conditions. Other studies for the mixed convection heat transfer in horizontal tubes with uniform heat flux boundary conditions for the laminar flow operating conditions include the experimental studies by Chae and Chung, Mohammed and Salman, Coutier and Greif, Bergles and Simonds and that of the numerical studies are the Boufendi and Afrid, Touahri and Boufendi and Piva. These studies indicated that both the internal heat transfer coefficient and friction factors characteristic of the tubes are much higher than those obtained by neglecting buoyancy-induced secondary flow. Lagana stated that pure forced convective heat transfer rarely occurred in practical applications since buoyancy forces usually exist in any forced convection, even at low temperature differences. Grassi and Testi experimentally investigated the turbulent mixed convection in the entrance region of a uniformly heated horizontal tube and developed heat transfer correlations for developing and fully developed flow for the turbulent mixed convection. Peyghambarzadeh experimentally investigated the effect of free convection on fully turbulent flow forced convection heat transfer in the thermal entry region of a horizontal tube with a constant heat flux. The Nusselt number for higher heat flux was higher than that of lower heat flux due to higher effect of secondary flow superimposed on the forced convection flow. Thus, these studies indicated that the secondary flow effects and heat flux distributions boundary type are very essential to be considered in determining the internal heat transfer and friction factors characteristics of an absorber tube if laminar or weak turbulent flow regime operating conditions are considered [26-30].

Discussion

Mixed convection heat transfer with asymmetrical heat flux distributions boundary

The earlier mentioned studies on mixed convection heat transfer were limited to cases where the heat flux distributions (whether uniform or not) are symmetrical in terms of direction of the gravitational field. In the laminar or weak turbulent flow regime, the secondary flow circulation patterns in absorber tubes could be mirrored on either side of the tube. When the non-uniform heat flux distributions boundary is asymmetrical in terms of the gravitational field direction, the buoyancy effects would result in different secondary flow paths. This indicates that the heat transfer characteristics of an absorber tube could be affected by the degree of asymmetry (Figure 4).

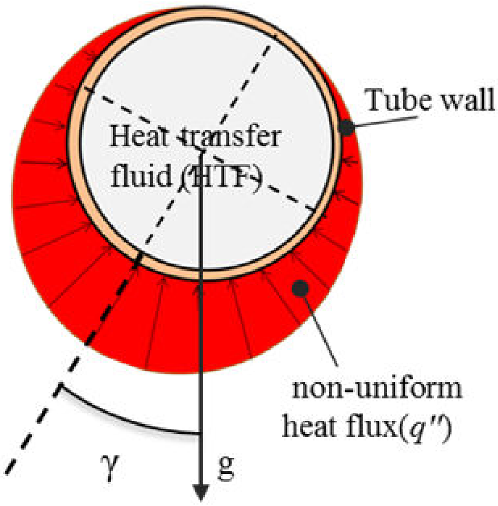

Figure 4. Asymmetrical non-uniform heat flux distribution boundary.

As shown in Figure 4, the asymmetrical non-uniform heat flux distributions boundary on the absorber tube occurs when the incident solar radiation has deviated from the zenith angle position resulting from the sun tracking system of the collector and if the receiver absorber misaligned with the focal line of the solar collector. This could have significant influence on the internal heat transfers as well as the friction factors characteristics of the absorber tubes. The impacts of the asymmetrical non-uniform heat flux boundary condition on the internal heat transfers, which will be present during majority of the day due to the sun-tracking system of the collector for the case of linear Fresnel solar collector type absorber tubes are lacking in the literature [31].

However, only few studies have considered cases of mixed convection asymmetrical uniform heat flux distribution boundaries for non-circular cross-sections, which are not applicable to circular tube based solar collectors, indicating the need to investigate the asymmetric heating in terms of gravity for a linear focusing solar collector tube. Some of these studies are briefly mentioned as follows. Bazdidi-Tehrani, numerically investigated the radiation effects on turbulent mixed convection flow between two the asymmetrically heated vertical parallel plates. They reported on the effects of wall emissivity and optical thickness on the fluid flow, thermal fields, Nusselt number, and friction factor. The wall emissivity and optical thickness increased the radiation effects on the centerline velocity, bulk fluid temperature and Nusselt number and friction factor decreased.

Satyamurty and Repaka in their study developed a superposition relation for calculating the local Nusselt number values for forced convective flow through asymmetrically heated parallel plate channels. The asymmetric thermal boundary condition was in terms of ratio of the wall temperatures in excess of the entry fluid temperature. They validated their model with numerical results and noted the model is valid as long as the geometric and flow symmetry are maintained.

Osborne and Incropera experimentally studied the laminar mixed convection heat transfer for water flow between horizontal parallel plates with uniform asymmetric heating. They reported that buoyancy driven flow had stronger effects on the bottom plate and low influence on top plate flow conditions, which indicated that forced convection heat transfer dominated at the top plate and mixed convection heat transfer dominated at the bottom plate.

Conclusion

This work has reviewed the convective heat transfer performance of the absorber tubes of linear Fresnel solar concentrating collectors. The studies reviewed were based on steady-state uniform solar flux distributions boundary assumption for convenience. This is contrary to the optical designs and ray-tracing simulations results, which indicated non-uniform solar flux distributions over the circumferential surface of an absorber tube. Studies are also lacking for the case of transient non-uniform solar flux distribution boundary condition. A number of experimental and numerical studies have investigated mixed convection heat transfer in horizontal circular tubes similar to that of linear Fresnel solar collector absorber tube, but were limited to uniform thermal boundary conditions. These studies indicated that due to buoyancy-driven secondary flow in the laminar and low turbulent flow regimes, the heat transfer rates and friction factor characteristics differed very significantly from pure forced convection cases. Studies are lacking for the case of non-uniform heat flux distribution boundary type encountered in a linear Fresnel solar collector system. Other applications where non-uniform wall heat fluxes are also encountered in circular tubes, which include conditions in boilers, are yet to be covered in the literature. No information could be found in the literature for the influence of asymmetrical non-uniform heat flux boundaries on mixed convection heat transfer characteristics for a linear Fresnel solar collector absorber tube. The asymmetrical non-uniform heat flux distributions boundary usually occurs in the solar thermal collectors when the incident solar flux has deviated from the zenith angle position and this could significantly influence the thermal performance of the absorber tubes.

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