UNIVERSITI PUTRA MALAYSIA

DESIGN AND ANALYSIS OF MEDIUM SCALE WATER PRODUCTION USING SOLAR PARABOLIC TROUGH COLLECTOR WITH TURBULATOR BAFFLES

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By

ALI JABER ABDULHAMED

Thesis Submitted to the School of Graduate Studies, University Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

November 2018

DEDICATION

This thesis is dedicated to:

My family whose support and understanding helped make this possible

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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November 2018

Chairman : Professor Ir. Nor Mariah Adam, PhD
Faculty ` : Engineering

Source of clean drinkable water is a big problem in the world. Water purification process consume the fuel which extremely effect on environment, economy, and human health. Solar parabolic trough collector (PTC) was built to meet the requirement of drinking water for the village members in a desert areas without relying on fossil fuel. The PTC powered by solar energy is the most favorable compared to flat plate because higher temperature is obtained. The design, fabrication, and performance of a stainless steel solar-powered parabolic trough collector (PTC) with a 90° rim angle and 3 m×1.314 m aperture area as a hot water generating system were investigated in this research. The gravity-load- and thermal-expansion-induced deformation of the receiver tube (δ_R) was also investigated. Comparing such deformation with the width of the solar image in the focal plane (w) revealed a maximum deformation of 1.43 mm in the mid length of the receiver tube that was within acceptable limits. The deformation of the receiver tube is an important new test to assess the thermal performance of PTC. The performance of PTC was assessed based on the ASHRAE Standard 93. In this work, thermal and thermodynamic performance of a receiver tube for a (PTC), heat transfer enhancement and pressure loss penalty for receiver exchangers equipped with baffles turbulator are experimentally and numerically investigated in a relatively low Reynolds number flow. Artificial obstructions on the underside of receiver tubes can increase the heat transfer coefficient between the receiver tubes (heat exchanger, HX) of (PTCs) and water as a working fluid. In this study, a numerically and experimentally tested the behavior of laminar mixed convective heat transfer in HX tube installed with baffles. These baffles are 20-rings that are connected together axially and connected radially to the inner tube surface. Using ANSYS FLUENT version 15.0, a performed computation fluid dynamics (CFD) modeling to achieve heat transfer enhancement in HX tubes equipped with turbulator baffles under laminar flow conditions were carried out. Moreover, the effects of pitch ratio (Pitch /Diameter) (P/D) = 3, 6, and 10 and Reynolds number $Re \leq 480$ were recorded. The novel application of the rings that are connected axially together and radially to the inner tube surface contributes to the long-term storage of thermal energy and promotes heat transfer via conduction from the tube surface to the center line of the water flow within a short period. In the study, the baffles generated a vortex to increase the Nusselt number (Nu) inside the HX. To simulate heat flux, a calculated the constant wall heat flux of the receiver tube using an electric heater. Results indicated that using 20 rings as baffles produces maximum heat transfer at Nu< 30 instead of plain tubes improves heat transfer by up to 75%. As P/D decreased and Re increased, the heat transfer rate, thermal enhancement factor (TEF) increased. The friction factor, TEF and the Nusselt number for the receiver tube with baffles were compared with those of plain tube without baffles under similar flow conditions to determine the heat transfer enhancement. The correlations for the Nusselt number, friction factor, and TEF were developed a PTC receiver tube equipped with artificial baffles. The developed system is capable of delivery 226 L/day water at ≥ 50℃.

Abstrak tesis yang dikemukakan kepada Senate Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

REKABENTUK DAN ANALISIS PENGHASICAN AIR SKALA SEDERHANA MENGGUNAKAN PENGUMPUL PALUNG PARABOLIK SOLAR DENGAN SESEKAT TURBULATOR

Oleh

ALI JABER ABDULHAMED

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Pembekalan air minum bersih merupakan satu masalah besar di dunia. Proses penyedian air bersih memerlukan bahanapi yang bauyak dengan memberikesan kepada persekitanan, economi dan kesihatanmanusah febu. Pengumpul palung parabolik (PTC) solar telan dibina untuk memenuhi keperluan air minum untuk sebuah perkampunpan oli kawasan pada pasir tanpa menggunakanbahan api fosil. PTC yang mengsunakan kuasa soar adalah lebih disukai berbanding pengumpul plat rata kerana suhu yang lebih tinggi mudah dincapai. Rekabentuk, fabrikasi dan prestasi pengumpul palung parabolik berkuasa solar yang diperbuat dari keluli tahan-karat (PTC) dengan sudut rim 90° dan kawasan apertur 3 m×1.314 m sebagai sistem penjana air panas telah dikaji. Beban graviti dan deformasi yang disebabkan oleh pengembangan haba tiub penerima (δ_R) juga turut diselidik. Membandingkan deformasi sedemikian dengan kelebaran imej solar dalam satah fokus = (w) menunjukkan deformasi maksimum 1.43 mm di bahagian tengah tiub penerima yang berada dalam had yang boleh diterima. Deformasi tiub penerima adalah satu ujian yang penting untuk menilai prestasi haba PTC. Prestasi PTC dinilai berdasarkan kepada ASHRAE Standard 93. Dalam kajian ini, prestasi haba dan termodinamik tiub penerima untuk (PTC), peningkatan peralihan haba dan penalti kehilangan tekanan untuk penukar penerima dilengkapi dengan turbulator sesekat dikaji secara eksperimen semasa nilai numerikal aliran nombor Reynolds yang rendah. Halangan tiruan di sebelah bawah tiub-tiub penerima boleh meningkatkan koefisien peralihan haba diantara tiub-tiub penerima (penukar haba, HX) (PTCs) dan air sebagai bendalirnya. Dalam kajian ini, ujian eksperimental dan numerikal perilaku peralihan haba konvektif bercampur laminar dalam tiub HX dipasang dengan sesekat. Sesekat ini adalah 20-gegelung yang bersambung secara paksi dan jejari kepada permukaan bahagian dalam tiub. Dengan menggunakan ANSYS FLUENT version 15.0, pemodelan dinamik bendalir komputasi (CFD) untuk mencapai peningkatan peralihan haba dalam tiub HX yang dilengkapi dengan sesekat turbulator dalam keadaan aliran laminar telah dijalankan. Tambahan lagi, kesan-kesan nisbah nada (Pitch /Diameter) (P/D) = 3, 6, dan 10 dan angka Reynolds $Re \leq 480$ telah dilaporkan. Aplikasi baru gegelung yang disambungkan secara paksi dan jejari kepada permukaan bahagian dalam tiub menyumbang kepada simpanan jangka panjang tenaga haba dan menggalakkan peralihan haba melalui konduksi dari permukaan tiub kepada garis tengah aliran air dalam jangka masa yang pendek. Dalam kajian ini, sesekat menjana satu vorteks untuk meningkatkan nilai angka Nusselt (Nu) dalam HX. Untuk merangsang fluks haba, fluks haba dinding yang malar pada tiub penerima diperolehi menggunakan sebuah pemanas elektrik. Keputusan menunjukkan bahawa dengan menggunakan 20 gegelung sebagai sesekat mengharilkan pemindalan haba maksinum pada Nu ≤ 30, dan bukan tiub biasa, ini boleh menambahbaik pemindahan haba sebanyak 75%. Apabila P/D berkurang dan Re bertambah, kadar pemindahan haba, faktor peningkatan haba (TEF) juga bertambah. Faktor geseran, TEF dan angka Nusselt untuk tiub penerima dengan sesekat dibandingkan dengan tiub biasa tanpa sesekat di dalam keadaan aliran yang sama untuk menentukan peningkatan pemindahan haba. Korelasi nilai angka Nusselt, faktor geseran, dan TEF telah membangunkan tiub penerima PTC yang dilengkapi dengan sesekat tiruan. Sistem yang dibangunkan itu mampu menjana air sebanyak 226 L/hari pada suhu ≥ 50℃.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the supervisory committee were as follow:

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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ASTM	American Society for Testing and Materials
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
A/C	Air conditioners
CFD	Computational fluid dynamics
CPC	Compound parabolic collector
CO_2	Carbon dioxide
3D	Three dimension
EHT	Enhancing heat transfer
ET	Eurotrough
FEA	Finite Element Analysis
FEM	Finite element method
FPC	Flat plate collector
Gr	Grashof number
Gz	Graetz number
PTC	Parabolic trough collector
TEF	Thermal enhancing Factor
HCE	Heat collection element
HTF	Heat transfer fluid
HX	Heat exchanger
ID	Inside diameter
IR	Infrared camera
MCRT	Monte Carlo Ray Tracing

Nu	Nusselt number
OD	Outside diameter
ORC	Organic Rankine Cycle
P	Pitch
PCM	Phase change material
PDC	Parabolic dish collector
Ra	Rayleigh Number
Re	Reynolds number
Rd	Diameter ratio
RO	Reverse Osmosis
SAHS	Solar air heating system
SIM	Simpson integration method
USA	United States of America
UMLVE	Unilateral milt-longitudinal vortexes
UHF	Uniform heat flux
UWT	Uniform wall temperature
UPM	Universiti Putra Malaysia
WHO	World Health Organization

LIST OF NOMENCLATURES

A	:	Area
A_a	:	Aperture area (m^2)
A_r	:	Receiver surface area (m^2)
A_f	:	Geometric factor
A_c	:	Cross section area (m^2)
A_s	:	Surface area (m^2)
C_R	:	Concentration ratio
C_p	:	Specific heat $(J/kg.K)$
D	:	Tube diameter (m)
D_i	:	Inside tube diameter (m)
D_o	:	Outer tube diameter (m)
f_L	:	Focal length (m)
f :	:	Friction factor
F_R	:	Heat removal factor
$\acute{F}$	:	Collector efficiency factor
g	:	Gravitational acceleration (m/s²)
Gr	:	Grashof number
Gz	:	Graetz number
h	:	Heat transfer coefficient (W/m² .K)
h_c	:	Depth of PTC (m)
I	:	Incidence sun radiation (insolation on the aperture) (W/m^2)
I_b	:	Extraterrestrial solar radiation

I_o	:	Solar constant (1366.1 W/m^2)
I_v	:	Current (Ampere)
k	:	Thermal conductivity (W/m .K)
L_{arc}	:	Arc length (m)
L_a	:	Latitude angle
L	:	Length of receiver tube (m)
$\dot{m}$	:	Fluid mass flow rate (kg/sec)
Nu	:	Nusselt number
Pr	:	Prandtl number
Q		Heat transfer (W)
Q_{loss}	:	Overall heat loss from receiver to the surrounding (W)
$q_{rad.}$	:	Maximum radiation heat transfer rate (W)
q_{cond}	:	Conduction heat transfer (W)
$q_{conv.}$	:	Convection heat transfer rate (W)
Ra	:	Rayleigh number
Re	:	Reynolds number
r_r	:	Maximum mirror radius (m)
r	:	Tube radius (mm)
S	:	The distance between the sun and the earth
S_o	:	The yearly mean earth-sun distance (1.496 × 10^{11}m)
T	:	Temperature (°C)
T_i		Inlet temperature of working fluid (°C)
T_o	:	Outlet temperature of working fluid (°C)
T_w	:	Surface plate temperature (°C)

T_∞	:	Fluid mean temperature (℃)
T_1	:	The wall temperature at face number one (℃)
T_1	:	The wall temperature at face number two (℃)
T_a	:	Ambient temperature (℃)
T_b:	:	Bulk temperature (℃)
T_m	:	Mean temperature (℃)
$T_{ave.}$	:	Average temperature (℃)
$T_{out}(t)$	:	Outlet temperature of collector fluid after time (*t*) (℃)
$T_{(out)f}$	:	Final outlet temperature of collector fluid (℃)
T_f	:	Average film temperature (℃)
t	:	Tube thickness (m)
u	:	Fluid velocity in tube (m/s)
u_{in}	:	Water inlet velocity (m/s)
U_L	:	Overall heat loss coefficient ($W/m^2.K$)
V	:	Voltage (V)
$\dot{V}$	:	Fluid volume flow rate (m^3/s)
$\dot{V}_p$	:	Volumetric flow rates in the tubes for plain tube (m^3/s)
w	:	Solar image display (m)
W_a	:	Aperture (m)
$\dot{W}_{pump}$	:	pumping power (W)
ΔP	:	Pressure drop (Pa)
$\Delta \boldsymbol{x}$	:	Wall thickness (m)
x	:	X-axis coordinate
y	:	Y-axis coordinate

Greek symbols

$\emptyset_r$	:	Rim angle (degree)
θ_z	:	Zenith angle
$\emptyset$	:	Angle at local mirror radius (degree)
a	:	Surface azimuth
a_s	:	Solar azimuth angle
β	:	Coefficient of volume expansion in unit (1/K)
β^*	:	Universal nonrandom error parameter caused by angular errors
η_c	:	Collector thermal efficiency
η_o	:	Optical efficiency
ω	:	Hour angle
δ	:	Solar declination angle
σ	:	Stefan-Boltzmann law, $(5.67 \times 10^{-8}\ W/m^2.K^4)$
v	:	Kinetic viscosity
σ_{total}	:	Total reflected energy distribution at normal incidence
σ_{sun}	:	Energy distribution standard deviation of the sun's rays at normal-incidence
σ_{slop}	:	Standard deviation of the distribution of local slope errors at normal-incidence
σ_{mirror}	:	Standard deviation of the diffusivity of the reflective material at normal-incidence
$\sigma^{\star}$	:	Universal random error parameter
μ:	:	Dynamic viscosity (kg/m.s)
μ_b	:	Dynamic viscosity at bulk temperature
μ_w	:	Dynamic viscosity at wall temperature
α	:	Altitude angle
ρ	:	Fluid density (kg/m³)

ρ_m	:	Reflectivity of reflector (Mirror reflectivity)
τ_c	:	Effective transmittance (Transmittance of cover material)
α_r	:	Absorptance factor (Receiver absorptivity)
γ	:	Intercept factor
i	:	Angle of incidence
d^*	:	Universal non-random error parameter
d_r	:	Receiver tube displacement from the focus of the parabola

Subscripts

a	:	Aperture, Ambient
arc	:	Parabolic collector arc
b	:	Beam, Bulk
c	:	Collector, cross
con	:	Connect
conv.	:	Convection
cond.	:	Conduction
f	:	Factor, Fluid, Film
F	:	Force
i	:	Inner, Inside
L	:	Loss, Length
m		Main, Mirror
N	:	Normal
o	:	Outer, Outside, Optical
P	:	Plain

R	:	Removal, Ratio
r	:	Receiver, Rim
rad	:	Radiation
s	:	Surface
w	:	Wall
z	:	Zenith
1	:	Wall face one
2	:	Wall face two

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays there is an increase in energy demand as a result of growing of population and the rising standard of living. By the year 2030, the world's energy demand is expected to increase by over 60% of current demand (Jebasingh & Herbert 2016). The use of fossil fuels as energy sources extremely affect the economy, environment, and human health (Shahin et al. 2016). Therefore, many countries tend to use renewable energy sources to meet their energy requirements without relying on fossil fuels, especially in water purification processes. Renewable energy is the energy from natural and unnatural sources including wind, biomass, solar, and waste heat energy generated through various human activities (Shahin et al. 2016). One of the most favorable renewable energy sources available today is solar energy.

According to the World Health Organization (WHO) report in 1984, for living standard, each person needs (3-5) liter of drinking water per day (Fiorenza et al. 2003; Eltawil 2008), the capita need at least 2 liters of hot water per day for household uses like coffee and baby formula. The production of hot water by using electrical heater still relies heavily on the use of fossil fuels to generate electricity and is the main factor in environmental pollution. Therefore, clean and alternative sources are needed for the production of hot water. Solar energy is an available and clean form of renewable energy used as an alternative to fossil fuels in generating energy. However, the maximum extraction of thermal energy from the sun is most challenging (Shahin et al. 2016).

A solar collector receive the sun's irradiation and transferred to heat energy, by increasing temperature or changing the phase of working fluid. Working fluid thermal energy can be utilized directly for different applications. Parabolic trough solar collectors (PTC) are a type of focusing collectors used to heat water or generate vapor. They consist of a reflective material in the shape of a parabola, a receiver tube, and support structures. The collector utilizes the solar rays from the sun, reflecting them onto the receiver tube which contains a heat transfer fluid (HTF) to produce hot fluid, as shown in Figure 1.1 (Shahin et al. 2016; Jafar & Sivaraman 2017).

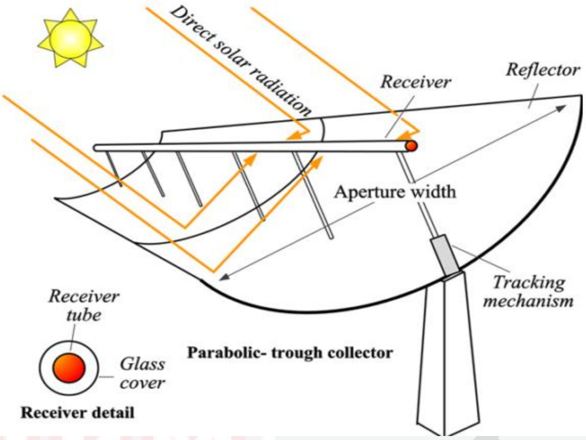

Figure 1.1 : Schematic of a parabolic-trough collector (Cabrera et al. 2013)

The PTC can be classified into two main groups of applications: for electricity generator and thermal applications for industrial processes (Jaramillo et al. 2016; Jafar & Sivaraman 2017). Concentrated Solar Power by using parabolic trough concentrator is one of the important renewable energy technologies for the generation of thermal energy for some industrial processes that requires temperatures between 85 and 250 ℃ (Fernández-García et al. 2010). These applications include distillation, evaporation, pasteurization, drying, cleaning and cooking, among others, as well as applications with low temperature heat demand and high consumption rates such as swimming pool heating, space heating and household hot water (Jaramillo et al. 2016).

Nowadays, researchers developed new devices using thermodynamic and technical economic analysis, and control methodologies to enhance the solar collector efficiency (Eskin 1999). The researchers also improved the reflective materials, absorber surfaces and receiver materials to augment the convection heat transfer coefficient in receiver tube working fluid (Choudhari & G 2013).

Generally, many techniques are utilized to enhance the heat transfer tube heat exchangers by increasing of fluid mixing, fluid vortices and turbulence intensity (Gholami et al. 2014). Many flow turbulators like baffles, wire coil and twisted tape have been used as tube/channel inserts to enhance turbulent, convection, and conduction heat transfer in the heat exchangers (Nanan et al. 2017). It is important to consider both of flow friction characteristics and heat transfer with one another to evaluate the thermal performance of receiver tube (heat exchangers H.X). Many researchers recorded that the flow friction characteristics and heat transfer are extremely dependent on turbulators geometry (Bellos et al. 2016).

1.2 Problem Statement

Clean drinkable water is a big problem in the world (Morad et al. 2015), therefore, two studies achieved at Universiti Putra Malaysia (UPM) to design and fabricate solar distiller system. Driver (2014) conducted research on parabolic trough collector (PTC) for portable solar water distiller system, with parabolic length of 1m (Driver 2014). Khiabani (2011) studied a numerical simulation of shell and tube heat exchanger as a condenser for portable distiller system. (Khiabani et al. 2011). All The reported works are at laboratory scale. There is a need to bring the work to an actual site and upscale it for water supply to village. Therefore, factors related to upscale must be studied. These factors include uncertainty, manufacturability and ability of PTC, wind load, and increasing performance of solar distiller by increasing Nusselt number.

Design and improve PTC system to produce 200 L/day of drinking water, needs to choose the low emmettance and high absorbance receiver tube material, and build reliable, repeatable, deliverable, and less maintenance system. It also need to Increase convection and conduction heat transfer inside receiver tube by increasing turbulant and vortex which taken place by using baffles, rings turbulator, or change the flow design for more than two passes. Increasing heat transfer inside receiver tube will led to a sub-problem of how to study the effect of free convection inside tube that using turbulator baffles. Especially, according to literature review the researchers who studied the design of PTC were conducted numerical and experimental study used glass enveloped as a receiver tube cover to reduce heat lost to the environment. Other researchers utilized Nano-fluid particles to enhance heat transfer in receiver tube. Researchers also deal with the shape of receiver tube (U-tube, elliptical, convex corrugated) to augment Nusselt number. However all reported studies did not use turbulator baffles to promote heat transfer coefficient in receiver tube of PTC (Menbari et al. 2017; Fuqiang et al. 2016; Behar et al. 2015; Nolte et al. 2015; Jafari et al. 2015; Wu et al. 2015; Cheng et al. 2015; Wang et al. 2015).

Researchers who using different geometries of turbulator baffles (ball, helical twisted belt, twisted tape, wire coil, vortex rings, and elliptic shape plat) which inserted inside tube to increase convection heat transfer in heat exchangers, they did not study the conduction heat transfer from inner surface of heat exchanger tube to the centre line of flow inside tube, these researches also studied only forced convection heat transfer in tubes. (Jasinski 2017; Sun et al. 2017; Jafar & Sivaraman 2017; Maradiya et al. 2017; Diwan & Soni 2015; Rivier et al. 2015).

Finally, many researchers studied the free or combine (free and forced) convection heat transfer in tube, however they usually use plain tube in mixed convection condition (Meyer & Everts 2018; Li et al. 2016; Hekmatipour et al. 2016; Colla et al. 2015; El Hasadi 2013; Feng & Li 2013; Li & Feng 2013; Allahyari et al. 2011).

Using electrical energy for water purification process still relies heavily on the use of fossil fuels which has the negative effect on human health, economy, and environment. Therefore, there is a need to use clean and alternative sources of energy to meet the requirement of the purification process. Solar energy is an available and favourable renewable energy that can use to fulfil the energy demands. However, the maximum extraction of thermal energy from the sun is most challenging (Shahin et al. 2016).

Flat plate collector (FPC) and parabolic trough collector (PTC) are two technique that used to convert solar irradiation to the heat energy in water as a working fluid. The maximum output temperature that obtained by utilizing FPC is 140℃ at best weather condition, however the productivity extremely reduce with windy, cloudy, and dusty weather (Zou et al. 2016; Morad et al. 2015; Kalogirou 2004). The PTC output temperature range are 350℃ to 400℃, and it can be work in the worst weather condition such as windy and dusty weather. Moreover, it can be work even under the condition of solar radiation of less than 310 (W/m^2) (Zou et al. 2016; Cabrera et al. 2013; Lüpfert et al. 2001).

This work will be considered the solar powered parabolic trough collector as a heat supply to the receiver tube. The research will also be considered the flow and the thermal mechanism of laminar mixed convection and conduction heat transfer inside receiver tube as a result of using turbulator baffles with low working fluid velocity $< 1(m/s)$.

1.3 Hypotheses

1) The new Nusselt number is equal to old Nusselt number for plain tube $(Nu_{new} = Nu_{old})_{Plain\ tube}$.
2) The new Nusselt number is more than old Nusselt number for tube equipped with baffles $(Nu_{new} > Nu_{old})_{tube\ with\ baffles}$.
3) Using turbulator baffles inside receiver tube for increase Nusselt number.
4) Increase reflector aperture area for increasing amount of incidence radiation receive.

1.4 Objectives

The aim of this work is to design and develop a PTC system that can produce 200 liter per day of hot water with temperature of more than 50℃ for household usage of village families in a desert area.

The specific objectives of the study are:

1) To develop mathematical model to produce 200 L/day heated water using baffles.
2) To design and analysis the receiver tube with turbulator baffles for enhancing heat transfer.
3) To validate the numerical model with experimental work.

1.5 Scope and Limitations

Designing solar powered parabolic trough collector for hot water generation with high efficiency is divided into two sub-projects as solar collector and receiver tube (heat exchanger). The (PTC) performance higher than flat plate collector, especially in a dusty weather in Baghdad-Iraq, due to the PTC has a wide range of temperature as high as 400℃ and received a large amount of falling radiation compared with other types of collectors. The current study is focused on designing, fabrication, and testing of PTC and receiver tube for desert climate of Baghdad.

The limitation of study are using theoretical calculation for design PTC according ASHRAE standard. The PTC receiver tube able to produce 200 liter per day of hot water with temperature more than 50 ℃ at ambient temperature range 36℃ to 53℃ as a result of using baffles turbulator. Nusselt number $Nu < 30$ required for computation of number of baffels rings to provide the required output in worst weather condition in Baghdad-Iraq. Therefore, the stainless steel (304) material will use to fabricate the receiver tube as PTC heat exchanger. The flow inside receiver tube is one-phase (liquid only), then using drinking water as a working fluid.

The scope of this study is to present accuracy design of parabolic trough collector with large aperture area and 90° rim angle follow ASHRAE guidelines 93. Furthermore, the study present design of receiver tube (heat exchanger) with 3m long and big tube diameter (50 mm) is commonly available; and to be easily fabricate, for cleaning and maintenance activities.

1.6 Thesis Layout

The thesis starts with introduction in chapter one. Chapter two includes literature review of solar collector especially PTC, as well as review of method enhancing heat transfer in tube with basic equations related to PTC and tube design and some important points that must be considered for designing PTC. Research Methodology is presented in chapter three with physical, thermodynamics and hydraulic mathematical calculation for heat exchanger and validation methods between experimental test and numerical/mathematical analysis. Chapter four presents a comprehensive explanation with all results related in designing of PTC and receiver tube. Chapter five presents the conclusion of this study and recommendation for future work.

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LIST OF PUBLICATIONS

Below publication articles based on this study:

A. J. Abdulhamed, N. M. Adam, M. Z. A. Ab-Kadir, and A. A. Hairuddin, “Review of solar parabolic-trough collector geometrical and thermal analyses, performance, and applications,” *Renew. Sustain. Energy Rev.*, vol. 91, no. April, pp. 822–831, 2018.

A. J. Abdulhamed, N. M. Adam, M. Z. A. Ab-Kadir, and A. A. Hairuddin, “Flow and thermal mechanisms in receiver tube of parabolic trough collectors with rings axially connected together and radially connected to the inner tube surface,” *Journal of Engineering and Applied Sicence.*, Accepted in 1-August-2018.

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