Numerical Investigation of Direct Absorption Solar Collector using Nanofluids: A Review

R. A. Rasih1,2, N.A.C. Sidik3*, and S. Samion2

1Faculty of Mechanical Engineering, Universiti Teknologi MARA Cawangan Johor Kampus Pasir Gudang, 81750 Masai, Johor, Malaysia
2School of Mechanical Engineering, Universiti Teknologi Malaysia, UTM Skudai, Johor, 81310, Malaysia
3Malaysia – Japan International Institute of Technology (MJIIT), University Teknologi Malaysia Kuala Lumpur, Jalan Sultan Yahya Petra (Jalan Semarak), 54100 Kuala Lumpur, Malaysia

*Corresponding author: azwadi@fkm.utm.my

Abstract. Research on direct absorption solar collector (DASC) has been quite intensive in the past decade. Solar thermal collector plays a vital role to determine the performance of DASC by utilized the heat transfer fluid to harvest the energy while the use of nanofluid (nanoparticle dispersion in a base fluid) enhanced the thermal conductivity. A lot of researchers have studied the influence of several parameters such as collector geometry and nanoparticle materials on the solar thermal collector efficiency for the past decade. This paper presents a recent progress on numerical modelling of nanofluid direct absorption solar collector (NDASC) for different type of geometry including flat type, parabolic trough and cylindrical tube. In this review, a more comprehensive numerical methods and solar collector geometry on NDASC are summarized. Finally, some recommendations are presented for future research guidance.

1. Introduction

The risk of energy shortage during (1970s) led to the tremendous research to seek new sources of energy [1]. One of the best ways to avoid this energy threat by utilized the solar energy, as it is free and sustainable. By 2050, 20% of low-temperature industrial heat process (<120 °C) is expected to run by solar energy which contribute to supply more than 3200 GW installed capacity per year [2]. On the next 50 years, it is anticipated that the advancement of solar technologies to provide about 70% of world energy consumption by 2100 [3]. Thus, a huge effort is required to increase the utilization of solar energy as it is significant to ease global warming, decrease environmental degradation and reduce greenhouse effect [4]. In addition, deteriorating of conventional fossil fuel indicates solar energy as the most prominent option to support current energy consumption.

Numerous studies have been conducted and invented new technologies to harvest the solar energy to enhance the performance of the system but the exploration to seek for the most efficient system is still demanding. Two most practical approaches to collect solar energy are solar thermal technologies which convert sunlight into heat energy using heat transfer fluid and absorber plate [5][6] while solar photovoltaic (PV) converts solar radiation directly into electricity through silicon based technology. Despite has longer lifespan and applied more recent solar technologies than thermal collector, photovoltaic (PV) collector has higher initial investment cost, more complex and requires a huge
installation space than its counterpart [7]. A more advance technology in solar energy using the combination of both collector called as photovoltaic-thermal collector (PVT) were carried out by other researchers [8][9][10]. This latest technology consists of PV module and absorber plate to convert simultaneously solar energy into electricity and heat. However, solar thermal collector still captures the interest of researchers and meet industrial purposes especially in water heating system due to its simplicity and practicality.

Kalogirou [11] in year 2004 reviewed several types of solar thermal collector which described thermal analysis, performance and practical applications but latest technology of PVT has been excluded. Meanwhile, Tian and Zhao [12] on 2013 covered the solar thermal collector, photovoltaic panel and latest PVT technology in their review. Solar thermal collector can be categorized into two: concentrating [13] and non-concentrating collector [14]. Concentrating solar collector focuses directly the sunlight into a single point through a certain focal length rather than its counterpart that only absorb the solar radiation using same intercepting area as its absorbing area without any optical element. Non-concentrating solar collector commonly used for domestic water heating and low temperature heating application while concentrating solar collector mainly used by high temperature solar collector.

Indirect absorption solar collector (IASC) is one of the popular methods to absorb the solar radiation through the absorber before heat transfer fluid (HTF) continues the heat conversion process. It was assumed that greater thermal efficiency could be achieved by increase the outlet temperature of solar thermal collector. To verify this assumption, vigorous studies on improvement of solar thermal collector efficiency have been conducted by several researchers [15][16][17]. Despite better thermal efficiency as compared to photovoltaic solar collector, high thermal resistance for energy conversion from the sunlight into working fluid becomes the main challenge of IASC. On the contrary, Minardi and Chuang [18] pioneered the concept of direct absorption solar collector (DASC). The key idea of this solar energy conversion concept is to reduce the thermal resistance between the heat transfer fluid and solar radiation by absorbs the sunlight volumetrically. The elimination of intermediate absorber improves the heat conversion process and increase thermal efficiency for solar thermal collector.

Recently, many researchers emphasized on the prospective of nanofluids (dispersion of nanoparticle in a base fluid) to obtain better thermal efficiency of solar thermal collector [19][20]. A more recent nanofluid called as binary nanofluid attracted several researchers [21][22] due to its synergistic effect to enhance thermal characteristics of heat transfer fluid. Several parameters including particle volume concentration, pH value and additives affected the nanofluid behaviour as an absorber fluid [23]. Despite better thermal behaviour to produce more uniform temperature distribution, the main concern of nanofluid is its stability at various temperatures, hence more investigations in this field are still demanding. Tyagi et al. [24] in 2009 started the concept of nanofluid in direct absorption solar collector followed by Otnicar [25] on the following year. Since then, many theoretical and experimental works on nanofluid direct absorption solar collector (NDASC) have been explored aggressively to obtain the best performance of solar thermal collector.

In the present paper, an inclusive review on the progress of numerical modelling of nanofluid direct absorption solar collector (NDASC) for different type of geometry is prepared with more precise. To the best of authors’ knowledge, there is no detailed literature on this subject. Several methods of solution to the numerical modelling also been discussed to assist future research on this area.

2. Nanofluid Direct Absorption Solar Collector (NDASC)
In 1975, the concept of direct absorption solar collector was started by Minardi and Chuang [18], followed by Huang et al. [26] who studied the solar thermal collector efficiency on a parabolic trough collector using black dye liquid water. Many studies then focus on the potential of DASC as compared to the indirect absorption. Few years later, Arai et al. [27] revealed that better heat transfer characteristics could be attained using fine particle suspension. There are vigorous studies on direct absorption solar collector (DASC) to be used in a wide variety of applications [28][29][30]. However, several problems experienced by conventional DASC such as clogging of pumps, pressure drops [31] and sedimentation. In addition, lower solar collector efficiency could be observed using typical fluids as an absorber mainly due to its weak absorption properties over the solar spectrum [32].
Meanwhile, the technology of nanofluid growth rapidly since it was introduced by Choi et al. [33] due to its better thermal characteristics as compared to the typical base fluid. Past literature revealed that nanofluid can exhibit low pumping power [33], higher thermal conductivity [34], adjustable fluid properties by concentration [34], better heat transfer characteristics [35], and higher specific heat capacity [36]. A more advance type of nanofluid called as binary nanofluid or hybrid nanofluid attracted several researchers due to its better thermal conductivity than using single nanoparticle [37][38][39].

In 2009, Tyagi et al. [24] started a numerical study to harvest the solar energy using nanofluids. By utilizing aluminium nanoparticles (<100 nm in size), an augmentation of thermal efficiency was observed as compared to flat plate collector under similar condition. This remarkable result attracted Otanicar et al. [25] on the following year who studied the same concept with different kind of nanofluid (graphite, carbon nanotube and silver with water as the base fluid). However, the improvement of thermal efficiency only can be attained by controlled several parameters such as volume concentration, size of nanoparticles, shapes and materials. Later, several studies focused on the effect of volume fraction and some researchers found that high temperature could be achieved even at lower volume concentration [40][41]. Besides volume fraction, thermal losses becomes a major concern for nanofluid direct absorption solar collector (NDASC) as it was believed to reduce the thermal efficiency even the fluid temperature increases [42][43]. Another problems difficulties of NDASC are stability of nanofluid at various temperatures, higher investment cost, erosion and sedimentation caused by nanoparticles. Despite this, little progress has been made to study NDASC using hybrid or binary nanofluid, a combination of more than one nanoparticles dispersed in a base fluid. Several researches [22][44] proved that the synergistic effect of binary nanofluids promising a better thermal characteristics on the solar collector than single nanoparticle dispersed in a base fluid. Therefore, research on direct absorption solar collector using hybrid nanofluid is suggested to enhance the understanding on this field.

3. Numerical model of Nanofluid Direct Absorption Solar Collector (NDASC)

Groundwork on theoretical model has been implemented by Tyagi et al. [24] who studied 2-dimensional analysis using finite difference method (FDM) to solve radiative transport equation (1) and energy balance equation (2):

\[ \frac{\partial l}{\partial y} = -K_{\text{ext, nanofluid}} l_x \]  \hspace{1cm} (1)

\[ k \frac{\partial^2 T}{\partial y^2} - \frac{\partial q_r}{\partial y} = \rho c_p U \frac{\partial T}{\partial x} \]  \hspace{1cm} (2)

where \( K_{\text{ext, nanofluid}} \) is the spectral extinction coefficient of nanofluid, \( l_x \) is the radiation intensity, \( k \) is the thermal conductivity, \( T \) is the temperature, \( \partial q_r / \partial y \) is the radiative heat flux, \( \rho \) is the density of the liquid and \( c_p \) is the specific heat. Otanicar [25] validated the previous model using different kind of nanofluids and then conduct an experimental setup to support their model. After that, research on NDASC has been conducted based on several popular numerical techniques such as finite difference method (FDM), finite element method (FEM), and finite volume method (FVM).

3.1. Finite Difference Method (FDM)

As finite difference method (FDM) is easy to implement, many researchers with different type of geometry condition also applied this method to solve the radiative transport equation (RTE) and energy balance equation [45][46][47][48][49][50][51]. Besides, a numerical code can be developed for structured spatial discretization for simple geometry such as flat receiver. However, most commercial software of CFD does not available on this method.

3.2. Finite Element Method (FEM)

Another techniques that widely used by most of the researchers to solve NDASC problem is finite element method (FEM) which discretizes the domain into finite elements and calculates the properties in every node [52][53][54][55][56]. This method is more numerically stable to solve a set of algebraic
equations. Besides, many commercial software packages use this method as it is efficient for different type of geometries.

3.3. Finite Volume Method (FVM)

Finite volume method including in ANSYS software has been used by many researchers [57][58][59][60] as it is best for regular geometries. As governing equations are solved using discrete control volume, this method is less stable compared to the FEM. Likewise FEM, lot of established and theoretically proven subroutines are in place for FVM which can be directly implemented in numerical code.

In 2018, Won and Lee [61] applied open source code using OpenFOAM to solve 2-dimensional heat transfer model. As it was new and easy to customize, OpenFOAM has pretty large number of solvers, utilities and applications including solar thermal collector. Table 1 shows the summary of numerical technique of past literature. These research were validated and show good agreement when compared with other literature data. Based on Table 1, it was shown that there are very limited studies on the turbulent flow as it was important for industrial purposes with high-speed velocity inside the pipe.
Table 1: Summary of numerical investigation of nanofluid in direct absorption solar collector.

| Author                  | Geometry | Nanofluid; Flow properties                                                                 | Numerical Solution                                                                 |
|-------------------------|----------|---------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Tyagi et al. (2009) [24]| Flat     | Al$_2$O$_3$/H$_2$O; Steady, uniform flow                                                   | Finite difference using MATLAB; 2-dimensional                                     |
| Zhu et al. (2010) [62]  | Flat     | SiO$_2$; and TiO$_2$ – water; Steady, laminar flow                                          | Simulation, radiative transfer equation solved using Rayleigh approximation; 2-dimensional |
| Otanicar et al. (2010)  | Flat     | Graphite, Carbon nanotube (CNT), Silver / H$_2$O; Steady, uniform flow                     | Improved numerical model by Tyagi et al. [24]; 2-dimensional                      |
| Otanicar et al. (2011)  | Flat     | Al$_2$O$_3$/H$_2$O; Steady, uniform flow                                                   | Improved numerical model by Tyagi et al [24]; 2-dimensional                      |
| Taylor et al. (2011) [64]| Flat     | Aluminium (Al), graphite (C), Copper (Cu), Silver (Ag) / Therminol VP-1; Steady, laminar flow | Numerical code; 2-dimensional                                                      |
| Lv et al. (2012) [65]   | Flat     | Graphite, solid metal and core shell / water; Steady flow                                   | Numerical code; 2-dimensional                                                      |
| Lee et al. (2012) [66]  | Flat     | SiO$_2$ cores coated with Au shell based in water; Au/water or Gold nanoshell (GNS) blended plasmonic; Steady, laminar flow | Monte Carlo method and Mie scattering theory to solve RTE, Finite element analysis; 2-dimensional |
| Ladjevardi et al. (2013) | Flat     | Graphite / water; Steady flow                                                              | Numerical code; 2-dimensional                                                      |
| Parvin et al. (2014) [52]| Flat     | Cu / water; Steady, laminar flow                                                           | Galerkin Finite element method; 2-dimensional                                     |
| Nasrin and Alim (2014)  | Flat     | Cu / water; Steady, laminar flow                                                           | Galerkin Finite element method; 2-dimensional                                     |
| Luo et al. (2014) [42]  | Flat     | TiO$_2$, Al$_2$O$_3$, Ag, Cu, SiO$_2$, graphite, carbon nanotubes / oil; Steady flow       | Simulation; 2-dimensional                                                          |
| Karami et al. (2014) [45]| Flat     | Single wall carbon nanohorns (SWCNH) / water; Steady, laminar                              | Forward difference implicit method; 2-dimensional                                 |
| Xu et al. (2015) [68]   | Parabolic trough | Cuo / Oil; Unsteady flow                                                                    | Commercial CFD software package; 3-dimensional                                   |
| Authors                  | Geometry | Working Fluids                                                                 | Flow Type       | Methodology                                                                 |
|-------------------------|----------|-------------------------------------------------------------------------------|-----------------|-----------------------------------------------------------------------------|
| Gorji and Ranjbar (2015)[57] | Flat     | Graphite / water; Steady, laminar flow                                         | Finite volume in ANSYS Fluent 15, 2nd order upwind, SIMPLEC algorithm for pressure velocity coupling; 2-dimensional |
| Nasrin et al. (2015)[54]   | Flat     | Cu / water; Steady, laminar flow                                              | Galerkin Finite element method; 2-dimensional |
| Moradi et al. (2015)[58]   | Cylindrical tube | Single wall carbon nanorhorn-water/EG; Steady, laminar flow                  | Finite volume method by ANSYS Fluent; 3-dimensional |
| Liu et al. (2015)[43]      | Flat     | Graphene/[HMIM]BF₄ (ionic liquid); Unsteady flow                             | Numerical integration, explicit by MATLAB; One dimensional, transient model |
| Chen et al. (2016)[46]     | Flat     | Silver, gold, titanium oxide / water; Unsteady flow                           | Finite difference method; One dimensional, transient model |
| Gorji and Ranjbar (2016)[59] | Flat     | Graphite, magnetite, silver / water; Steady, laminar flow                    | 2nd order upwind, ANSYS Fluent; 2-dimensional |
| Menbari et al. (2016)[47]  | Parabolic trough | CuO/Water; Steady, turbulent flow                                           | Finite difference method; 3-dimensional |
| Delfani et al. (2016)[48]  | Flat     | CNT/water-EG; Steady, laminar flow                                            | Implicit finite difference method; 2-dimensional |
| Chen et al. (2016)[69]     | Parabolic trough | CuO/Oil; Steady flow                                                        | UDF (User-Defined Function) of a commercial CFD software; 3-dimensional |
| Toppin-Hector and Singh (2016)[49] | Parabolic trough | Graphene and aluminium/Therminol VP-1; Steady flow                         | Finite difference method; 2-dimensional |
| Qin et al. (2017)[70]      | Flat     | Blended plasmonic nanofluid; Steady, laminar flow                           | COMSOL Multiphysics; 2-dimensional |
| Parvin et al. (2017)[55]   | Flat     | Cu-water nanofluid, Al₂O₃-water nanofluid, TiO₂-water nanofluid and pure water are used as the working fluid; Steady, laminar flow | Galerkin Finite element method (FEM); 2-dimensional |
| Kasseian et al. (2017)[60]  | Parabolic trough | MWCNT AND nanosilica / Ethylene Glycol; Steady flow                      | Simulation using Ansys Fluent; 3-dimensional |
| Hatami et al. (2017)[71]   | Flat     | Al₂O₃/H₂O; Steady flow                                                       | Hybrid of finite difference method (FDM) and Differential Transformation Method (DTM) - |
| Authors          | Geometry | Material(s)                                                                 | Flow Type                          | Methodology                                                                 |
|-----------------|----------|-----------------------------------------------------------------------------|------------------------------------|----------------------------------------------------------------------------|
| Hatami and Jing (2017) [56] | Flat (wavy collector) | TiO$_2$, Al$_2$O$_3$ and CuO / water; Steady, laminar flow | called Hybrid FDM-DTM - accuracy by 4th order Runge Kutta; 2-dimensional |
| Dugaria et al. (2017) [13] | Parabolic trough | Single wall carbon nanohorns / water; Turbulent flow | Finite element method (FEM) based on FlexPDE code; 2-dimensional |
| Won and Lee (2018) [61] | Flat | LSP or SiO$_2$ cores coated with Au shell based in water; Au/water; Laminar; Poiseuille flow | Monte Carlo method; Open Foam; 2-dimensional |
| Duan et al. (2018) [72] | Flat | LSP or SiO$_2$ cores coated with Au shell based in water; Au/water; | Volume integral method, implicit scheme; 1-dimensional analysis, transient model |
| Sharaf et al. (2018) [73] | Flat | Silver(Ag), aluminium (Al), graphite (G), copper (Cu) with base fluid water and Therminol VP-1; Steady, laminar flow | 2nd order Crank Nicolson method, MATLAB global optimization toolbox; 2-dimensional analysis |
| Siavashi et al. (2018) [74] | Flat | Single wall carbon nanorhorns (SWCNH)/water; laminar flow | multi- relaxation time, lattice Boltzmann method (MRT-LBM) code; 2-dimensional analysis |
| Freedman et al. (2018) [50] | Parabolic trough | Ag/Therminol VP-1; turbulent flow | Finite difference method; 2-dimensional (transform to Cartesian coordinate) |
| O’Keeffe et al. (2018) [75] | Parabolic trough | Aluminium/Therminol VP-1; laminar flow | Improved Crank-Nicolson Finite difference method; 3-dimensional analysis |
| Sharaf et al. (2018) [76] | Flat | Silver (Ag), aluminium (Al), graphite (G), copper (Cu) with base fluid water and Therminol VP-1; Steady, laminar flow | 2nd order Crank Nicolson method; 2-dimensional analysis |
| Garg et al. [51] | Flat | Graphite/water; steady flow | Finite difference implicit method (FDM) in MATLAB; 2-dimensional |
4. Conclusions

This paper presented numerical works done by previous researchers on nanofluid direct absorption solar collector (NDASC). As NDASC becomes more popular in solar thermal energy division due to its potential to generate better heat conversion process as compared to conventional surface absorber, the research in this field is still on going. Several numerical techniques have been used to study the theoretical model for the past decade. Finite difference method (FDM), finite element method (FEM) and finite volume method (FVM) widely used to solve radiative transport equation and energy balance equation to get the thermal efficiency of the system. In addition, most of the geometry of DASC focuses on flat geometry receiver, as it is simpler and more practical. However, there are still lacks of numerical model to study the turbulent flow at high concentration ratio. Besides, only one model considered wavy collector inside the flat rectangular channel. Therefore, some future researches on this field are suggested as follows:

- Recently, open source code using OpenFOAM gains more popularity because it is free CFD toolbox and many computational fluid dynamics including NDASC problems should be solved using this tool.
- A turbulent regime model should be analyzed properly to study the effect of nanofluids when enter the channel pass through the entrance and elbow of the channel which created fluctuation.
- A numerical analysis on binary nanofluid should be proposed for direct absorption solar collector as there are no literature data yet on this area.

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