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

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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 ^{O}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 Otanicar [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 Cuang [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 plat 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):

$$\frac{\partial I}{\partial y} = -K_{e\lambda,nanofluid} I_\lambda \tag{1}$$

$$k\frac{\partial T^2}{\partial y^2} - \frac{\partial q_r}{\partial y} = \rho c_p U \frac{\partial T}{\partial x} \tag{2}$$

where $K_{e\lambda,nanofluid}$ is the spectral extinction coefficient of nanofluid, I_λ is the radiation intensity, k is the thermal conductivity, T is the temperature, ∂q_r is the radiative heat flux, ρ 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 conducted 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_2O_3/H_2O; 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) [25]	Flat	Graphite, Carbon nanotube (CNT), Silver / H_20; Steady, uniform flow	Improved numerical model by Tyagi et al. [24]; 2-dimensional
Otanicar et al. (2011) [63]	Flat	Al_2O_3/H_2O; 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 nansohell (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) [67]	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) [53]	Flat	Cu / water; Steady, laminar flow	Galerkin Finite element method; 2-dimensional
Luo et al. (2014) [42]	Flat	TiO_2, Al_2O_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

Gorji and Ranjbar (2015) [57]	Flat	Graphite / water; Steady, laminar flow	Finite volume method 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]BF_4 (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, magnentite, 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, Al_2O_3-water nanofluid, TiO_2-water nanofluid and pure water are used as the working fluid; Steady, laminar flow	Galerkin Finite element method (FEM); 2-dimensional
Kasaeian 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	Al_2O_3/H_2O; Steady flow	Hybrid of finite difference method (FDM) and Differential Transformation Method (DTM) -

			called Hybrid FDM-DTM -accuracy by 4th order Runge kutta; 2-dimensional
Hatami and Jing (2017) [56]	Flat (wavy collector)	TiO_2, Al_2O_3 and CuO / water; Steady, laminar flow	Finite element method (FEM) based on FlexPDE code; 2-dimensional
Dugaria et al. (2017) [13]	Parabolic trough	Single wall carbon nonohorns / water; Turbulent flow	Monte Carlo method; Finite volume method using Ansys Fluent; 3-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 shceme; 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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