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Three-dimensional CFD simulations for Integrated Solar collector With Spherical Capsules Phase Change Material

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ABSTRACT

PCM system particularly play an important candidate at off peak to improve thermal storage system. This paper focus on provide a simple and useful tool to study energy performance of Integration of the Solar collector and Phase change material model by using computational fluid mechanics (CFD). A brief PCM numerical model including geometrical and operational parameters such as spherical capsules size, gap between spherical, the mass flow rate, charging and discharge time and wall temperature and discusses the effect this parameter on the output temperature. The working fluid temperature is uniform distributed and equal to output solar collector temperature. To simulate, a steady state energy balance has been applied to a control volume which basic equations have been solved by a finite element code with an iterative procedure over a wide range of conditions, and the results are incorporated into a correlation model.

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INTRODUCTION

With rising energy costs and an increasing demand for renewable energy sources as effective method for utilization of clean energy sources, especially solar energy. During the day the collected solar energy can be stored as sensible heat, latent heat, heat of reaction or a combination of these in materials such as water and rocks for passive and active heating applications. Therefore, the efficient and economical phase change materials (PCMs) are the main factor in utilization of solar energy in many applications such as heat buildings, eggs incubation, drying vegetables, meats, fruits, and other industrial purposes.

In recent years, thermal energy storage has attract several authors as a primary energy consumption concerning the application and modeling for domestic, commercial and industrial process (Tahat, M.A., 1995). Morison developed (Morrison, D.J. and S.I. Abdel-Khalik, 1978) transient behavior model to study the performance of phase change energy storage unit using both air and liquid as working fluid based on three assumptions such as axial conduction in the flow mode is negligible, Biot number is very low that temperature variations normal to the flow can be neglected, and heat loss from the unit can be ignored. The temperature levels and mechanisms of heat transfer dictate the geometry and design details of the system such as wall and roofs filled with PCM (Ismail, K.A.R., 1998; Henriiquez, J.R., 1996), control of electronic components, thermal protection and control (Ismail, K.A.R., J.N.C. Castro, 1997). Jurinak (Jurinak, J.J. and S.I. Abnel-Rualikt, 1998) proposed empirical method for sizing PCMs units for air-based solar heating systems for many locations during heating seasons. Tao (1967) presented a method for the analysis of solidification in cylindrical and spherical geometries based upon a fixed grid approach. Shih (1971) iterative method investigation for successive approximation to the solidification inside spherical geometry for large values of Stefan number and small Biot number. Additional numerical and experimental studies used for solving phase change problems are the enthalpy methods and temperature-based equivalent heat capacity methods (Zhang, Y., A. Faghri, 1996; Ismail, K.A.R., M.M. Abugderah, 2000; Zivkovic, B., I. Fujii, 2001; Sari, A., K. Kaygusuz, 2002; Kayansayan, N., M. Ali Acar, 2006; Prud Home, M., 1989; Cho, K., S.H. Choi, 2000).

In this paper, CFD analytic model for integrated solar collector and phase change material.A mathematical model was brief described including geometrical and operational parameters of spherical capsules PCM unit packed in cylindrical tubes inside a solar collector. Then investigate the optimum physical properties of the PCM on the thermal performance under a variety of loads and control strategies. In addition, aMatlab computer

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program also has been developed to compute the air temperature; spherical in each spherical PCM along with different collector dimension, charging time for each unit, and the time required to discharge all the thermal energy.

Physical model:

This system consists of three essential parts which are: a single transparent glass, isolated duct and thestorage unit is which consist of a single row of spherical capsules contain a PCM, the spherical capsules placed in thecrossflow of forced air stream, this unit works to satisfy two goals; absorb and storage the solar energy.The design take into consideration number of parameters such as, the integration with PCM storage unit, the simplicity of construction, dismantlement, and handling the PCM unit, the collector length which proposed by (Alkilani, 2009), and the number of spherical PCM at number of rows which controlled by the collector length. A solar simulator charge the collector by thermal energy until the spherical PCM became at liquidphase to investigate the output air temperature through assuming therewill be no conflict between charging and dischargingat differenttimes due to discharge process.

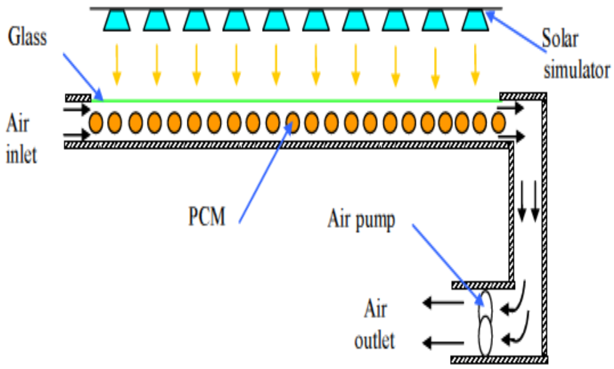

Fig. 1: Cross section of the solar air collector with PCM spheres (Alkilani, 2009).

For Heat Transfer Factor (HTF):

$$\varepsilon\rho_f A_c L c_f\left(\frac{\partial T_f}{\partial t}+v_{\max}\frac{\partial T_f}{\partial x}\right)=h_s a_p\left(T_p-T_f\right)+h_w a_W\left(T_W-T_f\right) \qquad (1)$$

Where:
A_c : The storage tank cross sectional area
C : Specific heat
L: Height of the storage tank
h_s: Surface heat transfer coefficient between HTF and PCM
T: temperature
T: time
V_{max} : HTF velocity
ε: Void fraction
x: Axial direction of the storage tank

The temperature of a planar surface subject to solar radiation, assuming that the surface behaves as a black body and that it does not lose heat to its surroundings by convection or conduction, is given as:

$$q_{solar} a_w - 2\sigma T_w^4 = 0$$

Where
q_{solar}: solar radiation flux
σ: Stefan-Boltzmann constant (5.67×10^{-8})
Where typical value for solar radiation flux is 1.140 Wm^{-2}.
For PCM:

$$(1-\varepsilon)\rho_p A_c L C_p\left(\frac{\partial T_p}{\partial t}\right)=h_s a_p\left(T_f-T_p\right) \qquad (2)$$

Where
ρ: density
Initial Conditions

$$T_f(t=0,x)=T_{f\_ini}$$

$$T_p(t=0,x)=T_{p\_ini} \qquad (3)$$

Boundary Conditions

$$T_f(t, x=0) = T_{f\_inlet}$$

$$\frac{\partial T_f(t=0,x)}{\partial x} = 0 \qquad (4)$$

Governing equations

Equations (1) and (2) are re-arranged to give the governing equations for computer programming:

$$\frac{\partial T_f}{\partial t} = \frac{\left[h_s a_p (T_p - T_f) + h_W a_W (T_W - T_f)\right]}{\varepsilon \rho_f A_c L c_f} - \left(v_{\max} \frac{\partial T_f}{\partial x}\right) \qquad (5)$$

and

$$\frac{\partial T_p}{\partial t} = \frac{h_s a_p (T_f - T_p)}{(1-\varepsilon)\rho_p A_c L C_p} \qquad (6)$$

Modelling Guides Using CFD Simulation:

The model with boundary conditions was converted to algebraic equations by means of finite-volume techniques with fully implicit temporal differentiation, using three-dimensional sphericalCapsulein a staggered arrangement. Delusive terms were evaluated using central differences scheme as shown in Figure 1.

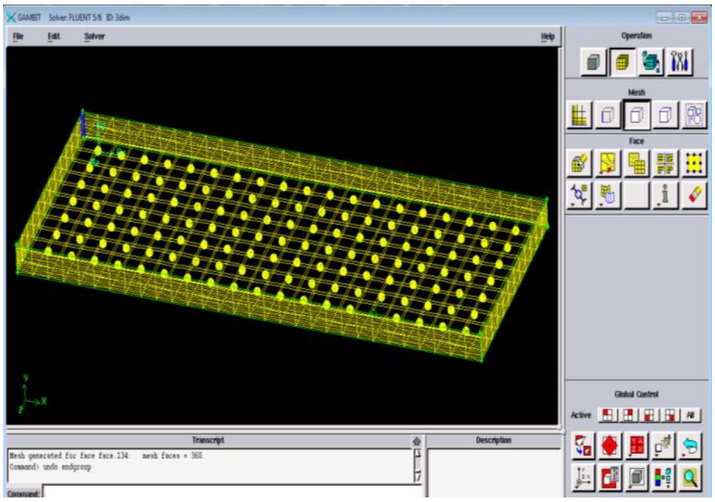

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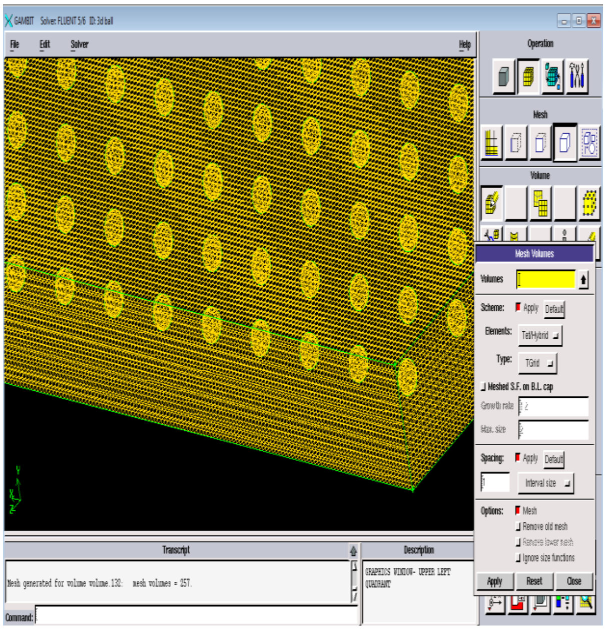
Fig. 1: Staggered arrangement CFD simulation model.



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Spacing: ■ Apply Default
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Options: ■ Mesh
☐ Remove old mesh
☐ Remove lower mesh
☐ Ignore size functions

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Mesh generated for volume volume.132:   mesh volumes = 257.
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GRAPHICS WINDOW- UPPER LEFT QUADRANT

Fig. 2: Spherical PCM CFD simulation model.

In practice, PCM characteristics and solution accuracy requirement together determine the best simulation strategy. The simulated system consists of a solar collector that can be opened or closed connected with inside opaque wall, insulated on the side facing the air space and with an external spherical-granite covering panel of the facade.

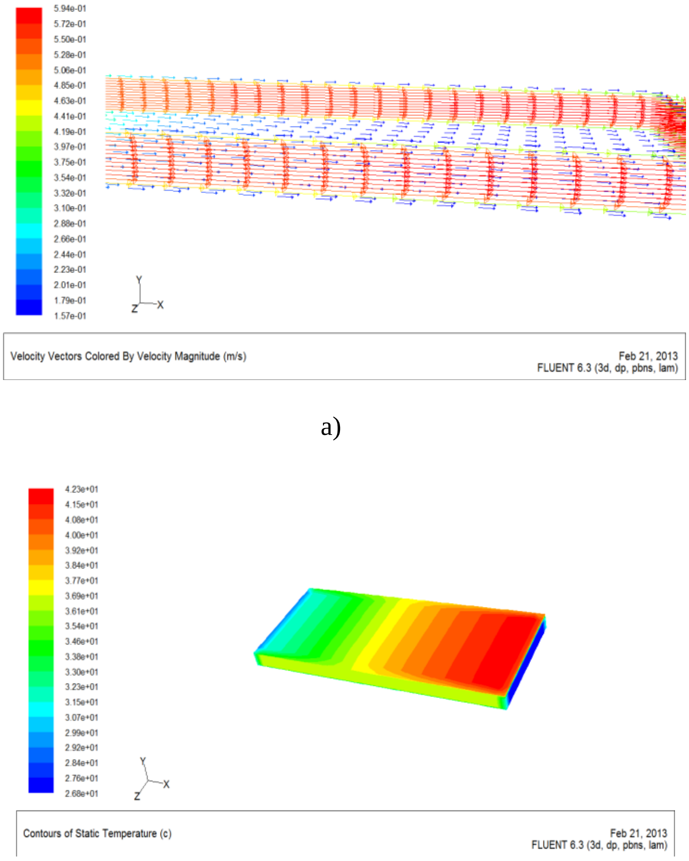
The following assumptions are made:

1. Two different domains for HTF and PCM with separate equations.
2. The HTF temperature is considered to be constant at the inlet during the entire charging process.
3. The PCM thermophysical properties are different for the solid and liquid phases.
4. The resistance offered by the thin wall of the spherical capsule is neglected
5. Initially HTF and PCM temperatures are considered to be uniform
6. The planar surface subject to solar radiation is assumed to behave as a black body and that it does not lose heat to its surroundings by convection or conduction.
7. The tank is perfectly insulated and heat loss from the tank surface to the surroundings is negligible.

Results Analysis:

The testing model parameters in Table 2,provided the dynamic boundary conditions such as supply airflow rate and surface temperatures for CFD simulation which effectively can predict the dynamic flow air velocity and temperature through PCM.

Figure 3a&b, shows the airflow pattern exhibits the typical flow characteristics through solar collector in which the airflow Velocity increase form min=0.157 to max=0.594m/s at time 2hr, and PCM temperature increase from 26.8 to 42.3^{o}C with Re=12073.



a)

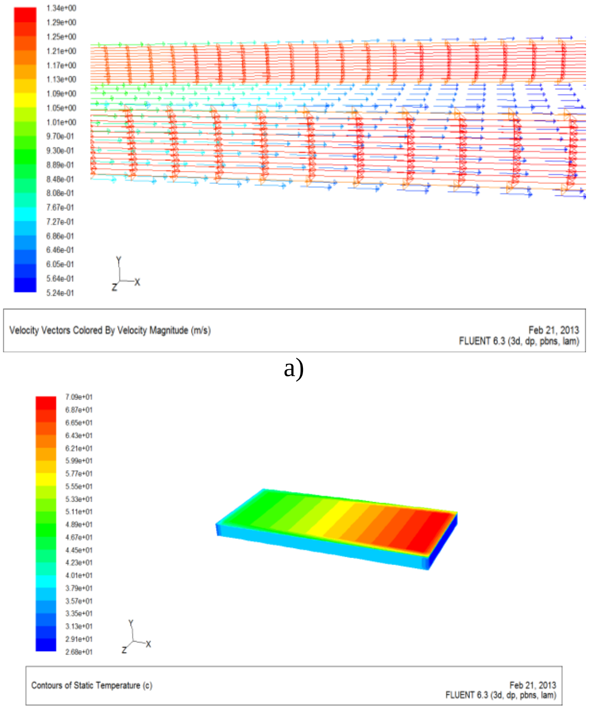
b)

Fig. 3: a) Airflow through solar collector b) PCM temperature distribution.

From figure 4a&b, with increasing Re=42751 both airflow will increase min=0.524 to max=1.34m/s to and temperature increase from 26.8 to 70.9oC.

Table 2: Testing model parameters.

Parameter	Value
Solar Collector	
Width	128cm
Length	300cm
Depth	10cm
Height	15cm
Spacing between each row capsules	0.2-0.4cm
Effective glazing area	217*120cm
Glass thickness	0.4cm
PCM	
Specific heat	2.5kJ/kg^{o}K
Capsule surface absorbance	0.97
Capsule surface emmittance	0.97
Kinematic viscosity	3.3-3.7mm^2/Sec. at 373^{o}K



a)

b)

Fig. 4: a) Airflow through solar collector b) PCM temperature distribution.

Conclusion:

With the aim of establishing basic guidelines for developing a new application of thermal storage PCM, in this study three-dimensional CFD simulation used for analyzes the integrated solar collector and PCM. The mathematical for heat transfer and flow characteristics model was developed to understand heat transfer mechanism relevant boundary conditions. In addition, different environmental also considered characteristics that may influence it necessity and effectiveness of applying CFD simulation. Finally, a particular emphasis is given to the validation of the mathematical model in order to quantify the level of temperature stratification inside the PCM storage devices. The CFD simulation provide a more accurate and informative prediction of PCM performance but needs a much longer computing time.

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