CFD SIMULATION OF DIFFERENT WATER TANK SHAPES ON TEMPERATURE DISTRIBUTION UNIFORMITY
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شبیه‌سازی CFD مخزن آب با شکل‌های متفاوت در یکنواختی توزیع دما

Ph.D. Stud. Eng. FarhadiR.[1], Lect. Ph.D. Eng. FarrokhiTeimourlouR.*[1], Lect. Ph.D. Eng. AbbasalizadehM.[2]
[1] Urmia University, Department of Mechanical Engineering of Biosystems / Iran;
[2] Urmia University, Department of Mechanical Engineering / Iran
E-mail: r.farrokhi@urmia.ac.ir

Keywords: *Disinfection, hydroponic, solar heat pipe, tank shape, uniform temperature distribution*

ABSTRACT
Reusing water drainage can effectively reduce water consumption in greenhouses. However, disinfection is unavoidable. A proper solar disinfection system needs uniform temperature distribution. Four different adiabatic tanks (prism, changed prism, cube and half-cylinder) were compared to achieve temperature distribution using a 3D computational fluid dynamics simulation. The tanks were equipped with solar heat pipes and their heat flux was assumed constant. A 30 minutes transient simulation was performed. The results showed that the cube tank had the most temperature uniformity, then the prism but with lower mean temperature. The changed prism and half-cylinder had almost similar effects and lower uniformity.

چکیده
استفاده دوباره از زه‌آب می‌تواند به طور موثر مصرف آب در گلخانه‌ها را کاهش دهد. اما ضدعفونی گریزناپذیر است. یک سامانه ضدعفونی خورشیدی مناسب، نیاز به توزیع یکنواخت دما دارد. چهار مخزن بیدرو مختلف (منشور، منشور تغییر شکل یافته، مکعب و نیمه استوانه با حجم یکسان) مقایسه شدند تا توزیع دما با استفاده از شبیهسازی سه بعدی دینامیک سیالات محاسباتی بدست آید. مخزن به لولههای حرارتی خورشیدی مجهز و شار حرارتی ثابت فرض گردید. سی دقیقه شبیهسازی گذرا انجام شد. نتایج نشان دادند که مخزن مکعبی و بعد از آن منشور ولی با دمای پایینتر، بیشترین یکنواختی را داشتند. منشور تغییر شکل یافته و نیمه استوانه تاثیرهای مشابه و یکنواختی کمتری داشتند.

INTRODUCTION
Clean and safe water is one of the most basic human needs. WHO-UNICEF (2015) reported that 663 million people still lack improved drinking water sources. “Although three-quarters of the earth’s surface is water, only 1% is available for direct use, and this often requires treatment before it can be used safely. Water contains many kinds of microbes and organisms, which can cause disease. It is estimated that 80% of all sickness and disease in developing countries is caused by unsafe water and inadequate sanitation” (*AniruddhaBhalchandra and JyotiKishen, 2013)*.

“Over the last 25 years, droughts covered more than 37% of EU territory and affected more than 100 million people. The total cost of droughts over the past 30 years amounts to more than 100 billion Euros” *(Andreu et al., 2014)*. Iran with dry and semi-dry region has water scarcity and approximately 92% of total water consumption pertains to agriculture (the ministry of energy, 2016). Wastewater treatment for agriculture has positive benefits and it is necessary due to water scarcity (EPA, 2012). Hydroponic system is one of the proper methods in dry regions. Reusing hydroponics water drainage can save 20 to 30 per cent in water consumption*(Tripanagnostopoulos and Rocamora, 2007)*. However, all of these need water disinfection.

One method that can actually kill pathogens instead of simply removing them is heat*(Burch and Thomas, 1998)*. Thermal energy can be supplied for disinfection by two nonrenewable and renewable resources. Nonrenewable resources of energy will finally finish and their prices have vicissitudes. In addition, global warming and climate changes are other disadvantages. Solar energy is a renewable, clean, free and sustainable resource. One of the existing methods to use solar energy is collectors. Solar heat pipe is an advanced collector and has some privileges: lower losses, higher efficiency, protected from freezing and overheating and absorbing beam and diffuse radiation *(Kalogirou, 2014)*.Thus it was selected in this study.

Various applications demand different temperature distribution in a storage tank. In some applications, such as for domestic hot water systems, stratification is attractive because, hot and cold water are separated inside a well stratified tank and this can improve hot water supply *(Alizadeh, 1999)*. However, for disinfection purposes a uniform temperature distribution is desirable, because pathogens must stand in a certain temperature for a while in order to be killed *(Feachem et al., 1983)*.

Temperature adjustment method has always a main contribution in the final decision related to the solar disinfection system. Some researchers have been applied solar collectors for disinfection purposes by various temperature controlling systems. *Bansal et al.(1988)*designed a solar collector where only near boiling water could exit from system. *Duff and Hodgson(2005)* made a solar water pasteurization system without valves. Water flow was adjusted based on density difference. Thermostatic valves have been used in some solar collectors to control output water temperature for disinfection *(Hameed and Ahmad, 1997; Bigoni et al., 2014)*.

Ali (2012) studied gained energy of two flat plate solar collectors (cylindrical and cubic shape) and recommended the cylindrical collector for continuous loading (tank has valves to supply required flow rate).

Yang et al. (2016) compared different tank shapes in cooling process to find which tank has more energy storage capacity and thermal stratification. They recommend sphere and barrel water tank for thermal energy storage and shapes with sharp corners for thermal stratification.

Heat source inside a storage tank tends to create two parts of cold and hot region, and nature of heat transfer tends to create uniformity. However, tank geometry can effect temperature distribution. Previous researches *(Joudi et al., 2004; Jordan and Furbo, 2005; Garnier et al., 2009; Oshchepkov and Frid 2015)* focused on stratification in a solar water heating systems. A solar collector designed for disinfection, especially with a non-continuous form, should provide a uniform temperature distribution. This paper attempts to show which tank shape has a more uniform temperature distribution.

MATERIAL AND METHOD

In this research, four tanks with different shapes (fig.1) and same volume (0.02940 m^3) were selected. The lengths of changed prism, cube and half-cylinderwere 0.9424, 1, 0.96105 and 0.95634 m, respectively. Tank walls were supposed to be in adiabatic state.

The condenser part of solar heat pipeis 60 mm long and its diameter is 14 mm. This part should be completely inside water as shown in the changed prism and cube tanks in fig. 1, but due to limitations caused by geometry and the angle of condensers, the whole part of condenser could not enter the prism and half-cylinder tanks (fig.1). There were five condensers in each tank and their distance was the constant value of 0.174 m. All five condensers in all tanks had the constant angle of 35 degrees with the horizon (all tanks were full of water).

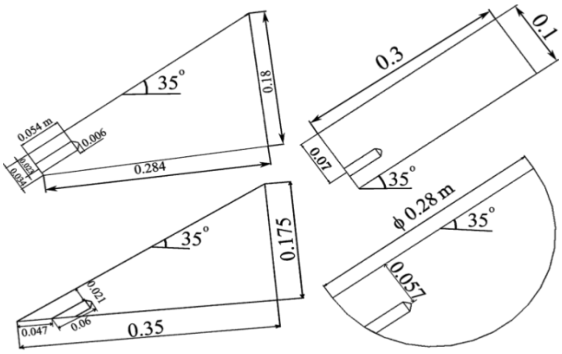

Fig.1 - Tank with different sections of changed triangle, rectangle, triangle and semi-circle (units: meter)

To measure heat flux of condensers, one solar heat pipe (length=1800 mm, Ø=58 mm,Deno solar equipment Co.) was exposed to the sun with the angle of 35^oon 9 March 2016 (location: 37°39'36.4"N 44°58'59.0"E) from 9:00 to 15:00, as is shown in fig.2, and the amount of energy (*q*) was calculate by equation (1). A small tank was placed on the condenser part and a small pump used to circulate the water. Two waterproof temperature sensors (DS18B20) were placed in inlet and outlet path and connected to by an electronic board to measure the temperature. The average of one-day data resulted in the flux of 20186 $W/m^2$and it was applied as a constant flux for simulations.

$$\dot{q} = \dot{m}c\Delta T = \dot{m}c(T_{out} - T_{in}) \quad (1)$$

Where:

$\dot{q}$: gained energy (J/s);

c: water specific heat (J/kg K);

T: temperature (K);

$\dot{m}$: mass flow rate (kg/s).

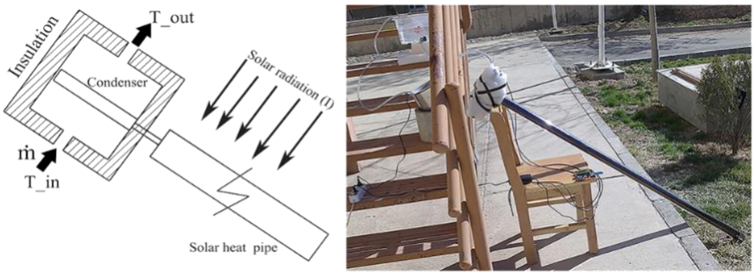

Fig.2 - Measuring condenser heat flux

A 3D computational fluid dynamics simulation was used by ANSYS-CFX software. A 30 minutes transient analysis with the k-epsilon turbulence was chosen. “One of the most prominent turbulence models, the k-ε (k-epsilon) model, has been implemented in most general purpose CFD codes and is considered the industry standard model. It has proven to be stable and numerically robust and has a well established regime of predictive capability. For general purpose simulations, the k-ε model offers a good compromise in terms of accuracy and robustness” *(ANSYS, 2013)*.Forasmuch as there is free convection, buoyancy model was activated. Initial water temperature inside the tank was set to 15°C. During simulation, tanks had constant water without any inlet or outlet flow. As geometry and boundary conditions were symmetric, the half part of tanks was considered in simulations and also in figures.

Results should not vary with different mesh numbers and time steps. Thus, the independency of mesh and time step were done as described by*Angermann (2010)*.

Two-sample Kolmogorov–Smirnov statistical test (*Dytham, 2011)* was used for comparing temperature distribution in different tanks using IBM SPSS statistics.

The results were evaluated by considering equation (1). Tanks had the constant mass of water (29.4 kg), heat flux was (20186 W/m^2), simulation total time was 30 minutes and initial water temperature was 15°C as mentioned above. Therefore, final uniform water temperature was calculated. The calculated temperature (expected uniform temperature in table 1 and table 2) was compared with the average temperature of all nodes estimated by the simulation.

RESULTS

Table 1 and table 2 present the results of mesh and time step independency. Meshes, which had lower difference with expected uniform temperature in table 1, were selected and used with different time steps. Expected uniform temperature in the prism and half-cylinder (table 1) was different from other tanks because, as described previously, the length of condenser in these tanks was different.

As can be seen in table 2, the results do not vary considerably by the time steps. In addition, standard deviation, coefficient of variation (CV) and standard error of mean in the table 1 and table 2 have low values representing results uniformity. Thus, for final simulation, the time step of one second was applied to discriminatemore accurately the temperature distribution.

Table 1

The results of simulation for different mesh numbers and tank shapes

Tank section	Element number	Mean temperature [K]	Standard deviation	coefficient of variation (CV) [%]	Standard error of mean	Expected uniform temperature [K]	Difference [%]
Changed prism	67493	291.4202	0.5277	0.1811	0.0048	294.95	1.20
	156837	291.6140	0.6949	0.2383	0.0040		1.13
	419100*	292.0197	1.1444	0.3919	0.0042		0.99
Prism	58300	290.8417	0.6672	0.2294	0.0065	293.93	1.05
	91860*	290.9510	0.5898	0.2027	0.0044		1.01
	597751	290.8510	0.5471	0.1881	0.0017		1.05
Cube	80500	291.3151	0.5216	0.1790	0.0061	294.95	1.23
	167416*	291.7085	0.8387	0.2875	0.0067		1.10
	578612	291.2710	0.3898	0.1338	0.0017		1.25
Half-cylinder	202446*	292.1846	0.9145	0.3130	0.0048	294.76	0.87
	393865	291.9053	0.7298	0.2500	0.0027		0.97
	718581	291.9717	0.8149	0.2791	0.0023		0.95

* selected mesh numbers

Table 2

The results of simulation with the selected mesh numbers for different time steps

Tank section	Selected element number	time step (s)	Mean temperature (K)	Standard deviation	CV (%)	Standard error of mean	Expected uniform temperature (K)	Difference (%)
Changed prism	419100	5	292.2311	1.0795	0.3694	0.0039	294.95	0.92
		10	292.0197	1.1444	0.3919	0.0042		0.99
		20	292.3350	1.1333	0.3877	0.0041		0.89
Prism	91860	5	290.9298	0.5980	0.2055	0.0045	293.93	1.02
		10	290.9510	0.5898	0.2027	0.0044		1.01
		20	290.7972	0.6105	0.2099	0.0046		1.05
Cube	167416	5	291.7649	0.8413	0.2883	0.0068	294.95	1.08
		10	291.7085	0.8387	0.2875	0.0067		1.10
		20	291.6504	0.8287	0.2841	0.0067		1.12
Half-cylinder	202446	5	292.2788	0.9029	0.3089	0.0047	294.76	0.84
		10	292.1846	0.9145	0.3130	0.0048		0.87
		20	292.1173	0.8988	0.3077	0.0047		0.90

Table 3 and table 4 show results with the time step of one second. All data have low standard deviation, CV and standard error of mean. It confirms uniformity of the results. However, velocity values have higher CV because in some parts of tanks water velocity is zero.

The cube and then the prism had the minimum value of variation in temperature and velocity. The changed prism and half-cylinder had similar conditions. The prism and half-cylinder had lower mean temperature as described for expected uniform temperature.

The temperature and velocity distribution are illustrated in fig. 3 and fig. 4 based on nodes data. The Kolmogorov-Smirnov test certified that all tanks had significantly different temperature and velocity distribution (table 5).

Table 3

The results of final simulation (temperature data)

Tank section	Mean temperature [K]	Standard deviation	CV [%]	Standard error of mean	Expected uniform temperature [K]	Difference [%]
Changed prism	291.9727	0.9367	0.3208	0.0057	294.95	1.01
Prism	290.5577	0.4849	0.1669	0.0033	293.93	1.15
Cube	291.2542	0.3142	0.1079	0.0022	294.95	1.25
Half-cylinder	291.7044	0.8880	0.3044	0.0059	294.76	1.04

Table 4

The results of final simulation (velocity data)

Tank section	Mean velocity [m/s]	Standard deviation	CV [%]	Standard error of mean
Changed prism	0.003893	0.002336	60	0.000014
Prism	0.003213	0.001847	57.50	0.000013
Cube	0.004207	0.002003	47.61	0.000014
Half-cylinder	0.003627	0.002184	60.20	0.000014

According tofig. 3, the best temperature uniformity belongs to the cube tank followed by the prism, changed prism and half-cylinder tanks. The prism tank had lower mean temperature because a little part of condenser was outside of the tank. Although velocity distribution in all tanks was statistically different, the cube and prism tanks had approximately similar distribution. The distribution was also the same in the half-cylinder and changed prism (fig. 4).It is expected that high velocity value assist to better temperature distribution *(Cengel and Ghajar, 2015)*as happened in the cube case (table 4). The higher velocity and flow in fluid will cause an increase in the mixture level and, consequently, result in higher uniformity.

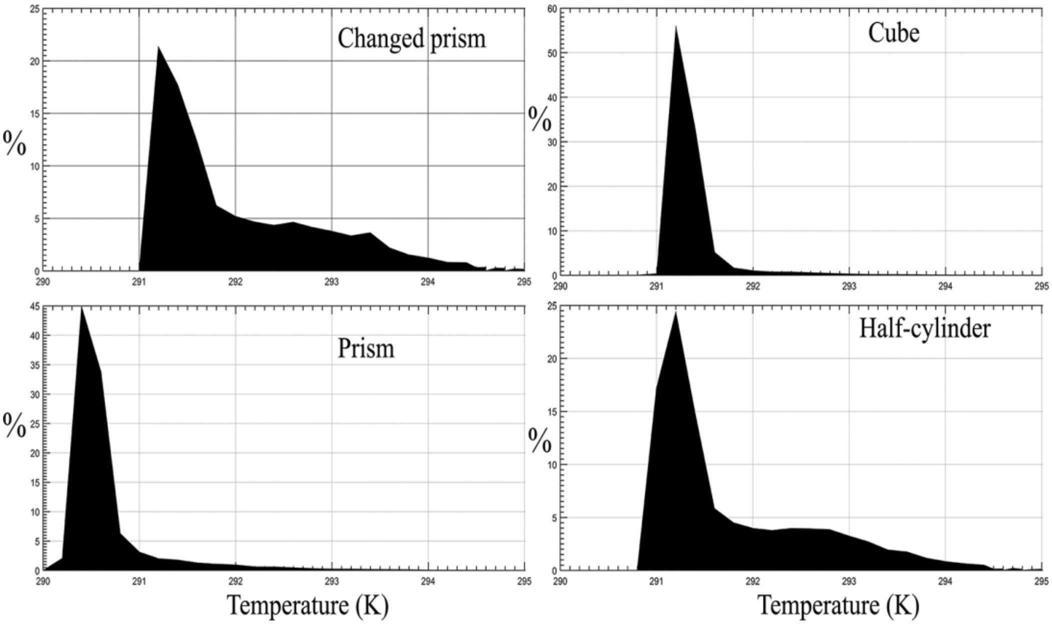

Fig. 3 – The histogram of nodes with different temperatures

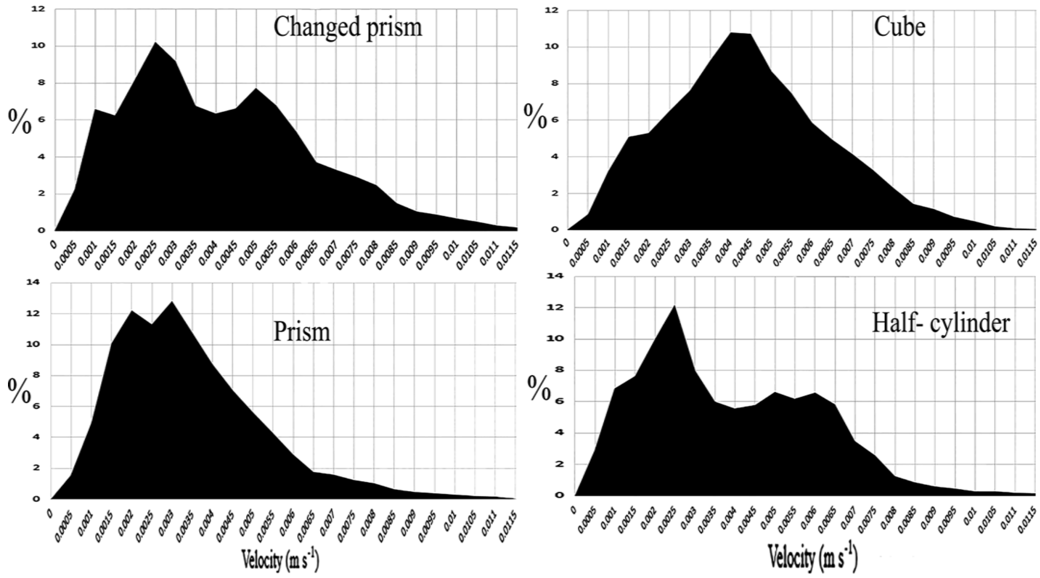

Fig. 4 - The histogram of nodes with different velocities

Table 5

Two-sample Kolmogorov-Smirnov test for comparing temperature and velocity distribution

Comparison item	**Kolmogorov-Smirnov Z**		***p*-valve**	
	Temperature	Velocity	Temperature	Velocity
Changed prism, prism	98.370	18.824	0.000**	
Changed prism, cube	54.196	15.503		
Changed prism, half-cylinder	30.529	6.734		
Half-cylinder, cube	34.581	20.301		
Prism, cube	92.089	26.756		
Prism, half-cylinder	91.839	15.509		

** p<0.01

It should be noted that the prism tank with lower mean velocity had proper uniformity because its mean temperature was lower than other tanks. For considering more details, nodes having top percentage in the fig. 3 are presented in fig. 5 (figures are the half of tanks due to symmetry). The picture confirms the similarity of changed prism and half-cylinder tanks, but cube tanks in right side perform differently. A vortex formed inside the tank disturbs uniformity (fig. 6). Although the cube tank had the best uniformity, reducing marginal space or optimizing condensers distance can boost uniform distribution. In addition, *Ali (2012)* recommended a cube tank in non-continuous flow for gaining more energy.

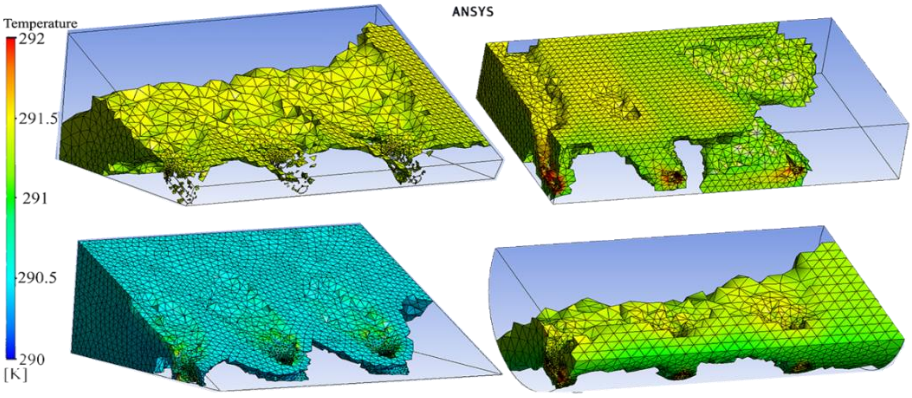

Fig. 5 - The location of most frequent temperature in each tank
(changed triangle and rectangle: 291.19-291.41 K, triangle: 290.39-290.61 K and semi-circle: 290.99-291.21 K)

As it can be seen from fig 5, the prism tank has apparently better conditions than the cube tank; although distribution data do not prove it. However, approximately 44.8 % nodes had lower temperature than the average in the prism tank while about 55% nodes in the cube tank were close to the average. Fig. 7shows nodes with the mean temperature of tanks. In these nodes, the volume of water in the cube was 13.1% higher than the prism tank(0.001244 m^3 in front of 0.0011 m^3). In addition, the nodes with mean temperature in the prism only occupied top parts of tank, while in the cube case, they were distributed in different parts. Therefore, all cases certify that the cube tank presents more uniformity. Furthermore, considering velocity in the prism tank reveals that most nodes of fig. 5 (prism) have low velocity.

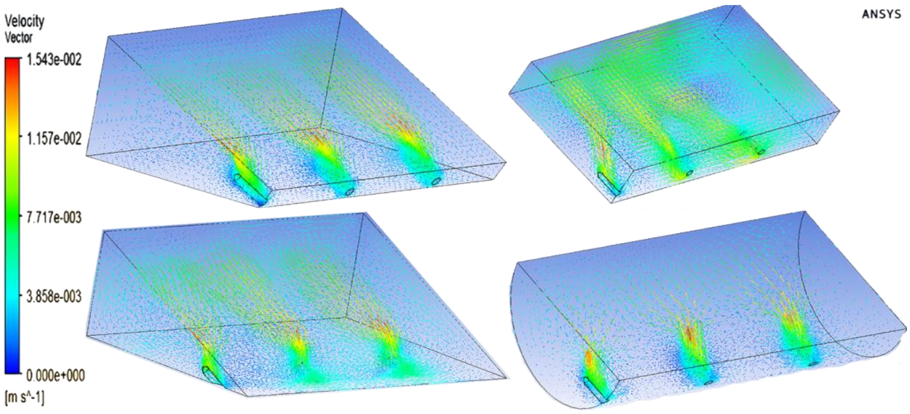

Fig. 6 – The fluid velocity in the tanks

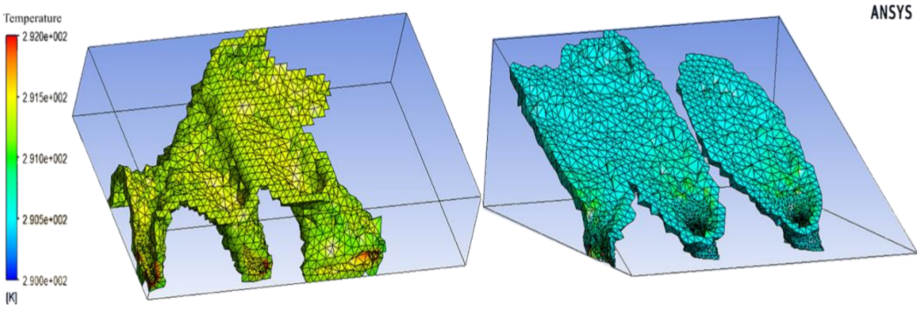

Fig. 7 – Nodes with mean temperature (rectangle:291.25, triangle:290.56 K)

In the symmetry and mid plane of the tanks,temperature contour plots (fig. 8 and fig. 9) show that the cube tank is different from others. It has the less stratified model while similar stratification exists in the changed prism and half-cylinder tanks, approximately. The prism tank has intermediate status among the tanks. *Yang et al. (2016)* reported similar status for tanks being in cooling process. It was proved that shapes with horizontal plane surface had lowest stratification.

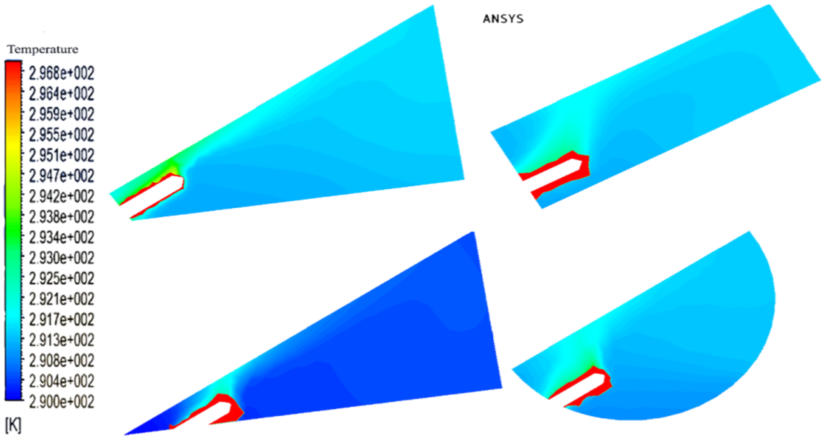

Fig. 8- Temperature contours on the symmetry plane

There is not adiabatic wall in nature; therefore, collected hot water at the top of condenser in changed prism (fig. 8) will be unsuitable for real applications due to heat losses.

All tanks had three regions with higher temperature placed above the condensers except for the cube tank having four parts (fig. 9). It increases temperature uniformity in the cube tank.

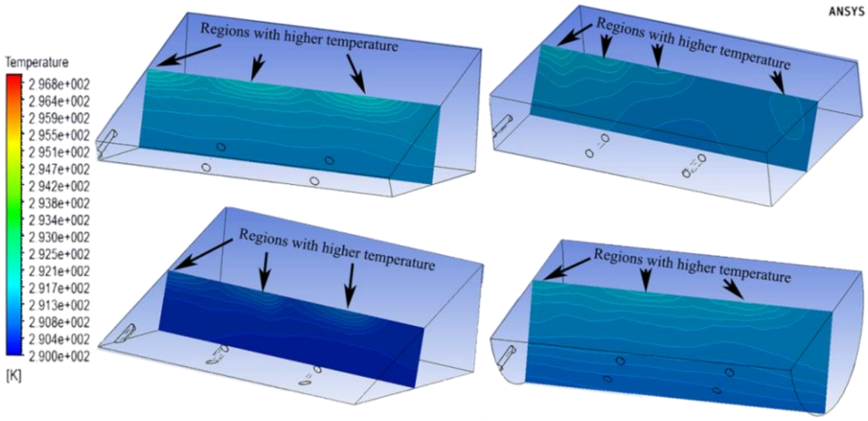

Fig. 9 - Temperature contours on the mid plane perpendicular to the symmetry plane

CONCLUSIONS

A 3D transient computational fluid dynamics simulation on a solar heat pipe collector with four tank shapes (prism, changed prism, cube and half-cylinder) was done. The collector had non-continuous flow, constant heat flux, adiabatic walls and natural heat convection. Comparing different tanks it has revealed that the cube tank had the best uniform temperature while the half-cylinder was unfit in temperature uniformity. Temperature distribution in the changed prism was similar to the half-cylinder and the prism had intermediate status. Since the tanks had maximum temperature variation in the start of simulation, first 30 minutes duration was selected in this study. The two-sample Kolmogorov-Smirnov test certified that distributions had statistically significant differences.Transient CFD simulation is time consuming and requires much time for reaching higher temperatures. Therefore, further experimental research should be conducted in order to analyze the operation of the proposed tanks for real disinfection temperatures (60-100°C).

ACKNOWLEDGEMENT

We would like to thank Dr. YoubertGhosta, (Department of plant protection, Urmia University) for his help and guidance during this experiment and research.

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