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Research paper

Numerical Investigations on Solar Chimney Inclination Angle for Room Ventilation

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Abstract

This paper presents a developed model of the roof solar chimney (RSC) and thermal performance predict using the simulation program Ansys Fluent 18 and solid work software 2016. This work is carried out under the climatic conditions of the city of Kut-Iraq. This study is based on the analysis the thermal performance of the solar chimney at different inclination angles (30^o, 45^o, and 60^o) with south and west direction. The results of the analysis showed that the solar chimney at a 45° angle gives the best thermal performance and provides a good ventilation rate. This model has been developed with the use of multi chimney tilted at a 45° angle in the same room. The arrangement of solar chimneys is in the two directions, one in the south and the second in the western direction. In this study, a several parameters were studied (angle of inclination, solar intensity, chimney direction, and ambient temperature), which significantly affect ventilation rates. The results showed that the use of the developed model leads to improved ventilation rates by 31.9 % and reduce average temperature are 1.34 ^{o}C.

***Keywords**: Natural ventilation, Multi chimney, roof solar chimney, thermal performance.*

1. Introduction

Natural ventilation using a solar chimney is a simple means to provide comfortable thermal conditions for occupants of the space. The ventilation is operated by buoyancy force due to incident radiation on the absorber, which increases the temperature of the air inside the solar chimney and thus increases the flow of air upwards and allow the entry of new air into the space.

Majid H. M. et al. [1] conducted an experimental investigation to solar chimney utilized as a heating supply in Iraqi environmental condition has been done. Experimental room bound under a certain size (2.5*1.29*1.07) m, the studying model source with a solar collector 40° tilt angle south facing. The results were taken through January and February at different positions in the test zone. The walls towards sunlight can enhance the stored energy. Enhancement heat energy assists to make more motive force to flow rate air inside the supposed building. Hussain H. Al-Kayiem et al. [2] investigated the experimental sides were carried out employing a rectangular duct comprising a flat plate-glass cover with the following dimensions: 2 m length, 0.07 m depth,0.48 m width. The measurements were done at inclination angles of 70°,50°, and 30° to locate the optimum angle of the absorption-free convection mechanism. The optimum slope angle to achieve the better collector performance was found to be 50°. Al-Kayiem et al. [3] An analytical study of the solar chimney model was carried out on the upper surface. The study was carried out using the simulation of the mathematical model. They found that system performance is greatly affected by the intensity of solar radiation. Mahdavinejad et al.[4] presented a numerical study with use simulation program cities in Iran and for different climates. The results indicate that the ideal angle of the solar chimney is 45 degrees, which can reach the maximum amount of ventilation rates. The ventilation rate is minimum when the solar chimney is vertical in all the cities studied, except the cold climate city of Tabriz. Nadia .S. et al.[5] presented a numerical and experimental study of natural ventilation using a solar chimney. The solar chimney angle variation of (30 - 40) degrees, as well as the different air gap between the absorber plate and glass are used (10, 20, and 30) cm. The results show, that the thickness of the air gap has a significant effect in increasing air flow significantly and reached to optimal thermal pull in the chimney angle of tilt of 45 degrees. Ahmed A. I. et al.[6] conducted experimental and numerical study was used to obtain the best performance of the solar chimney under different geometric characteristics. A turbulent flux was used for natural convection. This flow was at different angles (15°- 60°) and solar radiation (150-750) W/m^2 with a three air gap of solar chimney (50, 100, and 150) mm. The results showed that the maximum ventilation rate occurs at the optimum inclination angle 60° at 750 w/m^2 intensity with 50 mm air gap. Chung et al.[7] presented optimum values of parameters which influence performance of solar chimneys. The outcome indicate to that optimum air gap ranges from 0.6 m to 1.0 m, chimney length of 1.5 m to 2 m and induced air velocity from 0.04 m/s to 0.22 m/s. The ventilation rate increase by 24% when the air gap is 10 cm and the angle of inclination increases from 15 to 45 degrees.

This study aims to knowing the thermal performance of the multi solar chimney and improving the ventilation rates through two different models using the simulation programs (Ansys Fluent 18) and software solid work 2016. The first model contains a room connected with a solar chimney with angles (30°, 45° and 60°). The second model includes two solar chimneys with 45° inclined angle of the same room.

2. Problem Statement

The reliance on mechanical cooling, especially in the summer, increases the operating time of cooling devices in order to obtain appropriate thermal conditions inside buildings. The period of operation has a negative role in the environment and increase pollution in addition to the economic implications. Passive cooling is an appropriate solution to reduce energy consumption in the building sector and reduce the risk of pollution .Therefore, Iraq is considered to be one of the countries where solar radiation is suitable quantities (2000 - 2500) kWh/m^2. This paper will research the possibility of solar chimney (one of the means of passive cooling) to provide appropriate ventilation rates for occupants of the space.

3. Numerical Analysis

The theoretical study includes of the following sub-sections, computational domain, the governing equations, mesh generation, and boundary conditions. In addition, validation of present numerical study and another previous numerical study has been discussed.

3.1 Computational Domain

In the present study, it was used two model of solar chimney. The first theoretical model consists of a room made of wood connected to a inclined solar chimney at an angle (30°, 45°, and 60°) and dimensions (0.3*1*1) m. This chimney has of three facets of glass thickness of 4 mm and the other side consists of absorber made of aluminum material with 1 mm thickness and insulation material thickness 50 mm with 8 mm wood. The roof of the room is covered with insulation material thickness 25 mm as shown in Figure (1, 2, and 3). The Table (1) is explained the thermal specifications of the materials used. The room has a window with dimensions (0.3*0.3) m located in the north wall for the purpose of entering the air during the work of the solar chimney. All this cases or models will be simulated using the program (Ansys Fluent 18) and two different directions (south and west).

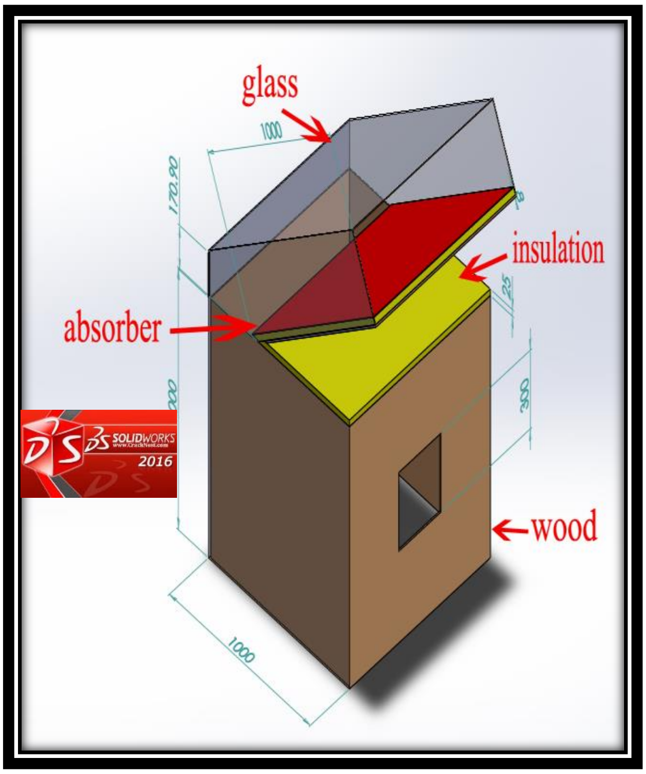


Figure 1: Roof solar chimney with inclination 30^o (all dimensions in mm)

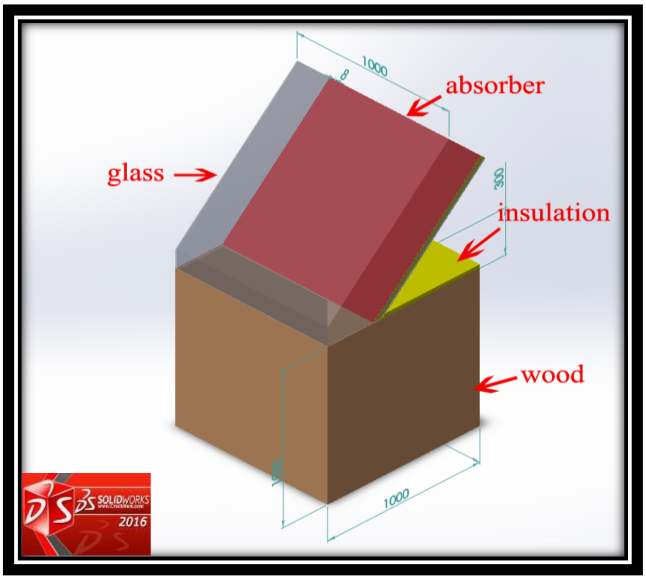


Figure 2: Roof solar chimney with inclination 45^o (all dimensions in mm)

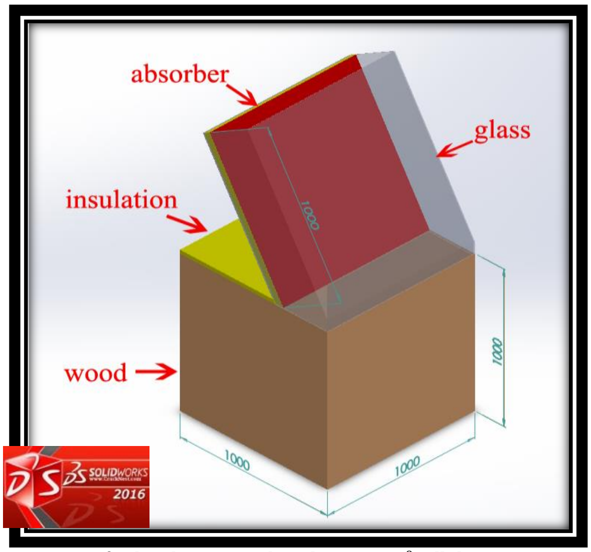


Figure 3: Roof solar chimney with inclination 60^o (all dimensions in mm)

Table 1: Thermal properties materials

n	Materials	Thickness mm	ρ (kg/m^3)	Cp (kj /kg-k)	k (W/m-k)	α	ε	τ
1	Glass	4	2220	0.83	1.15	0.06	0.95	0.84
2	Absorber plate	1	2700	0.9	237	0.95	0.95	0
3	Wood	8	400	1.8	0.06	0.5	0.5	0
4	Insulation	50	52	0.657	0.038	0.4	0.4	0

The second model or (second case study) are developed by using two solar chimney tilt with angle 45° on the roof. One in the south direction and the other in the western direction as shown in Figure (4).

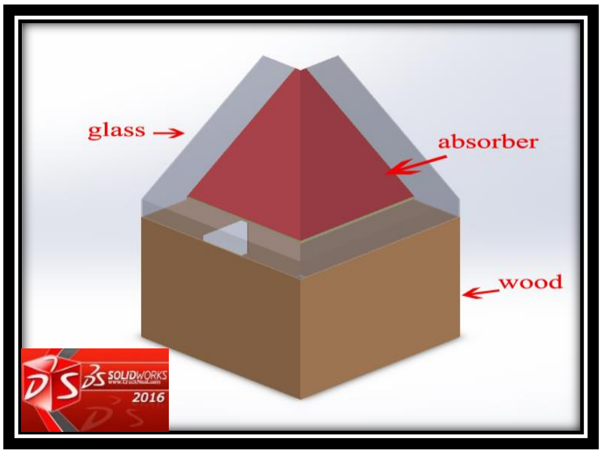


Figure 4: Two Roof solar chimney with inclination 45°

3.2 Governing Equations

In this study, a set of equations is used to solve the model by Ansys Fluent 18 software. Which is used continuity, momentum conservation, energy conservation and radiation equations to regulate calculations the behavior of fluid flow and heat transfer:

Continuity equation

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho \vec{v}) = 0 \qquad (1)$$

Conservation of momentum

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \vec{\nabla}.(\rho \vec{v}\vec{v}) = -\vec{\nabla} P + \vec{\nabla}.\vec{\bar{\tau}} + \rho g \qquad (2)$$

Conservation of energy

$$\frac{\partial}{\partial t}(\rho E) + \vec{\nabla}.[\vec{v}(\rho E + P)] = \vec{\nabla}.k_{eff}\vec{\nabla} T + \vec{\nabla}.(\bar{\boldsymbol{\tau}}_{eff}.\vec{v}) \qquad (3)$$

The radiation transfer equation

The radiation transfer equation (RTE) is used to absorb, dissipate and emit the site $\vec{r}$ and move in the direction $\vec{s}$

$$\frac{dI(\vec{r},\vec{s})}{ds} + (a + \sigma_s)I(\vec{r},\vec{s}) = an^2\frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r},\vec{s})\Phi(\vec{s}.\vec{s}')d\Omega' \qquad (4)$$

3.3 Mesh Generation

The precise design of the mesh system is critical to predicting heat transfer results in advanced engineering. The distribution of mesh lines and their intensity plays an important role in obtaining more accurate results. The type of mesh used in this study is a combination of (tetrahedron) and (hexahedron). The number of mesh up to more than 4 million cells to obtain more accurate results as shown in Figure (5).

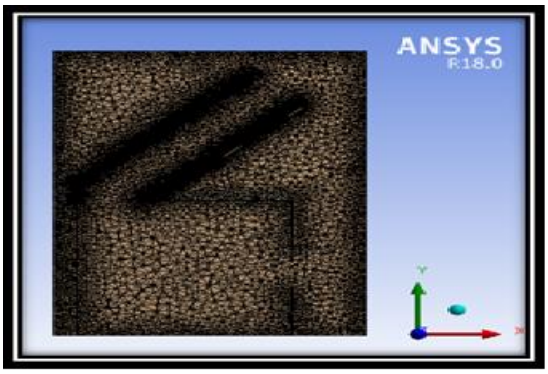


Figure 5: Mesh generation

Choosing the optimum mesh

In order to obtain accuracy in the solution and for a suitable period of time, mesh were created five sizes of a different three-dimensional in (Ansys fluent 18) software to the tilted solar chimney 30° angle model at 14 pm. After conducting simulations for all sizes shown The optimum mesh was (4051373) elements, Through which it was obtained accurate results as shown in Table (2 and 3).

Table 2: Choosing the optimum mesh

n	Hour	Elements	Nodes	ACH	Temperature
1	14	1096497	195057	6.52	321.67
2	14	2335325	422436	7.2	321.806
3	14	3074193	557567	7.43	321.6
4	14	4051373	867859	7.53	321.4
5	14	5432508	964168	7.59	321.13

Table 3: Mesh information

n	Domain	Elements	Nodes	Tetrahedron	Hexahedron
1	absorber	15500	31500	0	15500
2	domine	3362765	635339	3337281	0
3	glass	207765	69818	207295	0
4	insulation	390886	84056	366310	0
5	wood	56197	19174	56197	0
6	wood_1	18260	27972	0	18260
7	All Domains	4051373	867859	3967083	33760

3.4 Boundary Conditions

Figure (6) shows the room connected to chimney consisted cubical wooden with dimensions (1*1*1) m and covered with insulated on the roof. The solar chimney consisted from channel has a glass facade is allows the radiation to enter the chimney to heat the absorbent. Aluminum is used as a heat-absorbent panel. The boundary conditions are applied according to the climate data of the city of Kut Table (4). In these study cases are used pressure inlet, pressure outlet (atmospheric pressure) and no-slip condition between the fluid and wall. A standard k-ω turbulence model associated with the laws of the wall along solid boundaries is employed. The solar incident radiation was simulation by the Discrete Ordinates (DO) model. The SIMPLEC algorithm is used for coupling of continuity and pressure. The walls are non-adiabatic heat transfer by conduction, convection and radiation consideration. The theoretical results are obtained from the 8 Am to the 6 Pm for the day (15-6-2016).

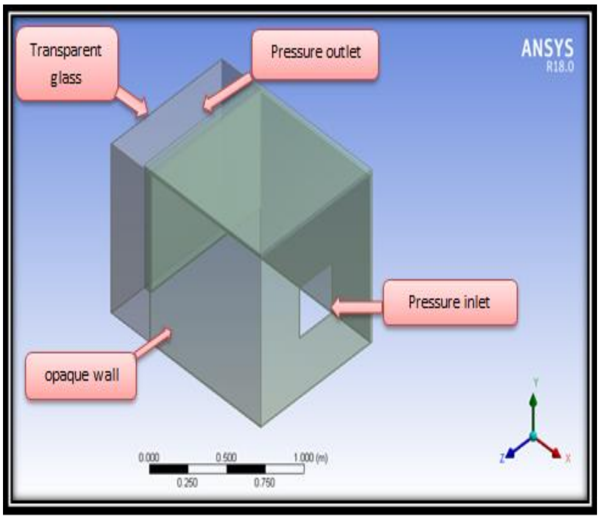


Figure 6: Boundary condition of models

Table 4: Data for the climate of the city of Kut (15-6-2016)

Date	AT Max C°	AT Min C°	RH Max %	RH Min %	SLR Avg W/m²	SLR Total Mj/m2
15-Jun-2016 18:00	42.64	41.28	8.08	6.09	182.48	0.66
15-Jun-2016 17:00	43.16	42.45	8.18	5.24	219.94	0.79
15-Jun-2016 16:00	43.54	42.93	7.98	5.52	222.39	0.8
15-Jun-2016 15:00	43.77	43.22	7.98	5.34	726.83	2.62
15-Jun-2016 14:00	43.82	42.87	7.8	5.36	847.98	3.05
15-Jun-2016 13:00	43.12	42.24	8.33	5.74	909	3.27
15-Jun-2016 12:00	42.29	41.23	9.44	6.29	899.1	3.24
15-Jun-2016 11:00	41.32	39.56	12.9	7.25	846.26	3.05
15-Jun-2016 10:00	39.59	37.41	15.43	11.27	751.02	2.7
15-Jun-2016 09:00	37.43	34.23	16.72	11.71	611.72	2.2
15-Jun-2016 08:00	34.23	30.79	19.08	14.15	439.5	1.58

4. Validation of the Present Study

For the purpose of ascertaining the work of the mathematical model in Ansys Fluent software, A validity has been established with the previous studies, Bassiouny Ramadan et al. **[8]**, Mathur et al. **[9]**, and David Park **[10]**. In figure 7 it can be seen that there is a good agreement between the current results and previous studies with acceptable error is (1.42% - 14.12%).

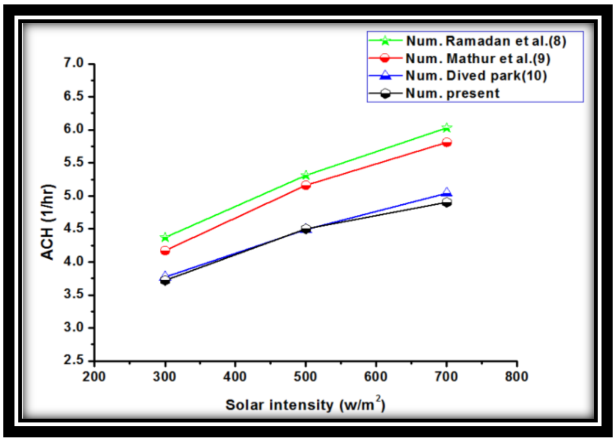


Figure 7: Validation of computational analysis graph

5. Results and Discussions

In this section the results are showing the effect of solar intensity and solar chimney direction on ACH and average room temperature of two models or two case studies of solar chimneys where the figure (8) represents the solar intensity rate on 15-6-2016. As follows.

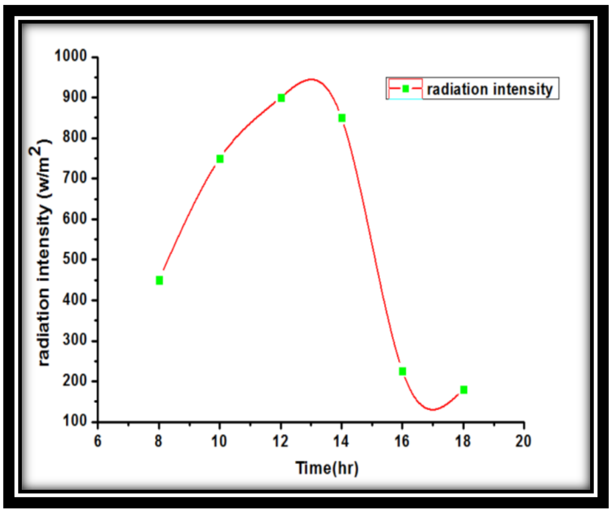
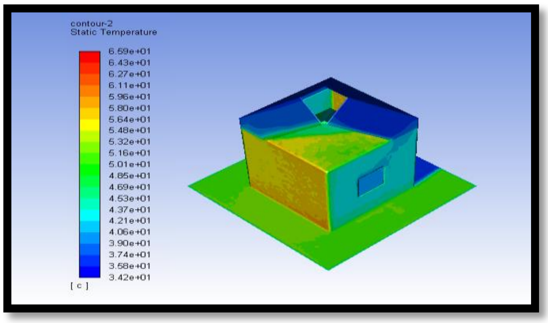


Figure 8: Variation of solar radiation with time

Figure (9-14) shows the effect of solar intensity during the day on the developed model



Figure(9): Hour 8 am

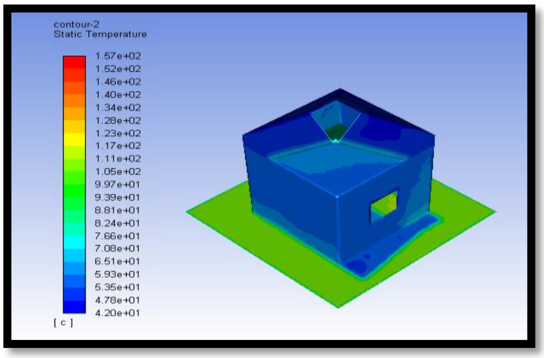


Figure (10): Hour 12 noon

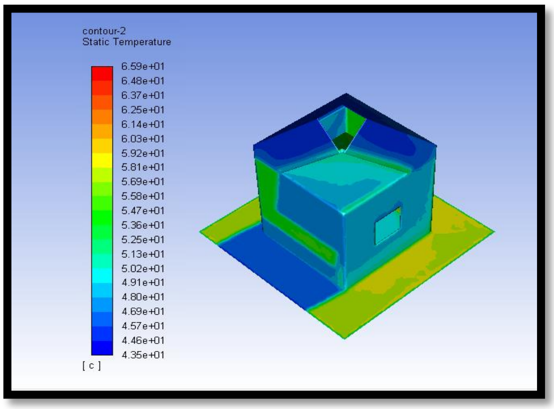


Figure (11): Hour 16 P m

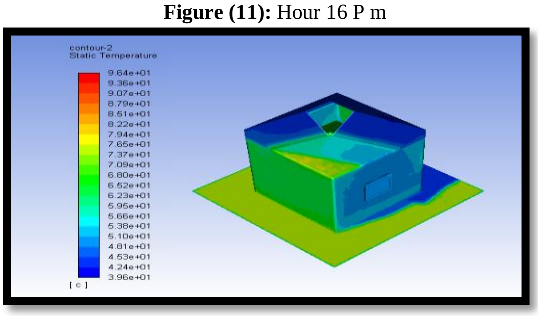


Figure (12): Hour 10 am

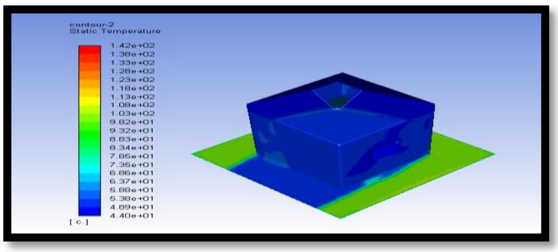


Figure (13): Hour 14 P m

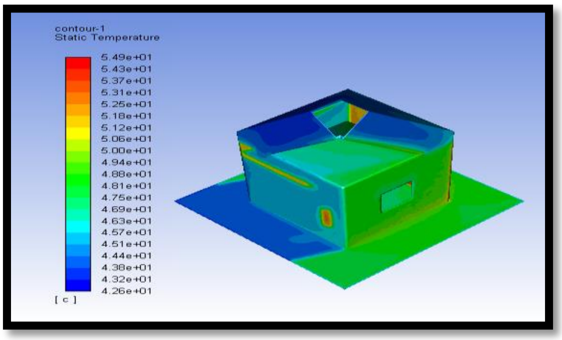


Figure (14): Hour 18 P m

5.1 The First Study Case (First Model)

This case study includes the effect of solar intensity, the direction of the solar chimney on ventilation rate and the temperature in the room.

5.1.1. Effect Solar Intensity and Solar Chimney Direction on ACH

Figure (15 to 20) is showing the effect of solar intensity and solar chimney direction on ACH for different angles of solar chimney (30°, 45°, and 60°). Figures 15 and 16 illustrated this effect in the case of the solar chimney angle 30°. Figure (15) shows for an increase in ventilation rate in solar chimney southern with increasing solar radiation and ambient temperature up to 14 pm. This is agreement with previous studies. At 14 pm the ventilation rate reaches maximized as a result of increased solar intensity and direction as well as increased ambient temperature, this lead increases the effect buoyancy force. After 14 pm the ventilation rate decreases until to 18 pm, notice the increased ventilation rate again because heat transfer from western wall and entry solar radiation into the room through the window. This causes rise the air temperature in the room and thus increasing the ventilation rate due to buoyancy force effect. In addition, to pulling the chimney.

In the case of changing the direction of the solar chimney towards the west, it was noticed that the ventilation rate is 8 am greater than the ventilation rate at 10 am due to the entry of solar radiation from the window where it leads to high temperature of the air inside the room and thus increase the ventilation rate. At 12 noon the ventilation rate is maximum because of an increase the buoyancy effect, where the hot air rises upward through the chimney. After this time the ventilation rate starts to decrease until 18 pm and then, the ventilation rate is increasing again because the orthogonal direction of the solar radiation on the absorber.

Figure(16) shows the contour of the velocity in the southern chimney at 14 pm at which the highest occurs the ventilation rate.

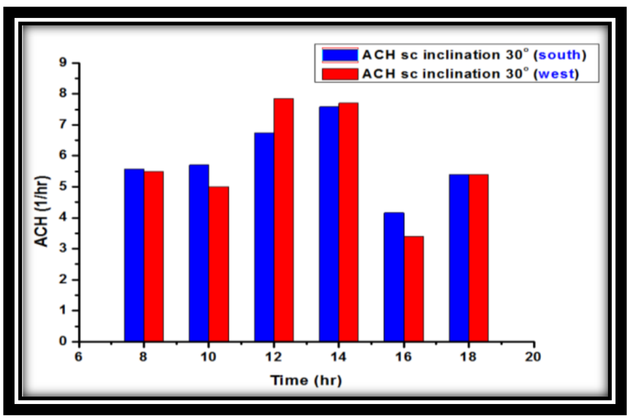


Figure 15: ACH of roof solar chimney inclination 30°

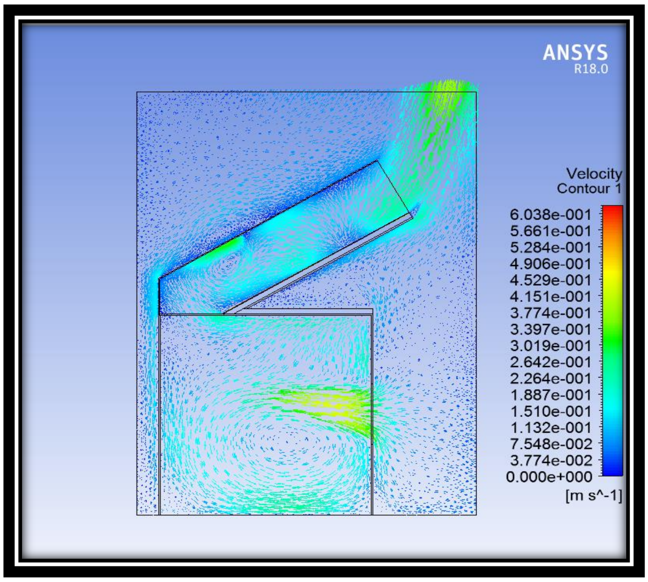


Figure 16: Contour of velocity at 14 pm in southern direction

Figure (17 and 18) Illustrates the thermal performance of the solar chimney at angle of 45°. Note that the rate of ventilation in the solar chimney to the south direction has gradually increased from 8 am with the increase of solar intensity and direction until 10 pm. At 10 pm the solar intensity reaches the high value (750 w/m^2) which causes heating absorber and thus increase the temperature of the air inside the solar channel and this leads to the rapid flow of air to the top due to increased effect of buoyancy force. After this time, the ventilation rate decreases gradually due to the change direction solar intensity falling on the absorbent until 18 pm. At this time, the ventilation rate increases slightly due to the entry of part of the radiation into the room.

When the solar chimney in the west direction the ventilation rate of 8 am is greater than at the south direction as a result of the introduction of a larger section of the radiation into the room. Thus, the increase in air temperature will lead to greater air flow rate. At 12 am the ventilation rate reaches the maximum value due to the exposure of the solar chimney to an appropriate amount of radiation, in addition to the large transfer of heat from the southern wall into the room through conduction, convection and radiation. So, there are two forces of pulling the chimney and increase effect of buoyancy force. After this time only the effect of pulling the chimney due to the radiation perpendicular with absorber will result in gradually decreasing the ventilation rate until 18 pm. Figure18 shows the contour of the velocity in the southern chimney at 10 am at which the highest occurs the ventilation rate.

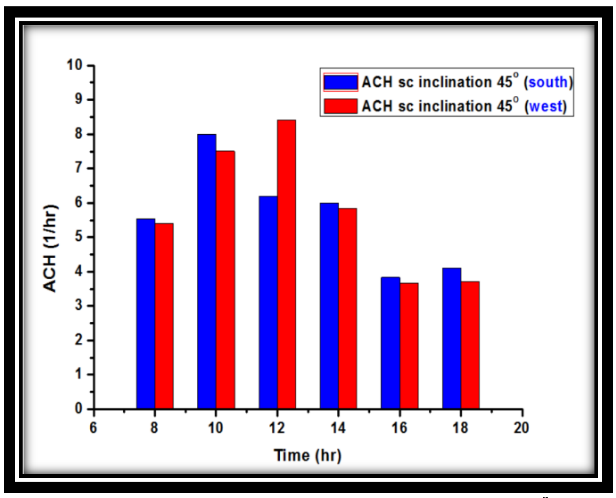


Figure 17: ACH of roof solar chimney inclination 45°

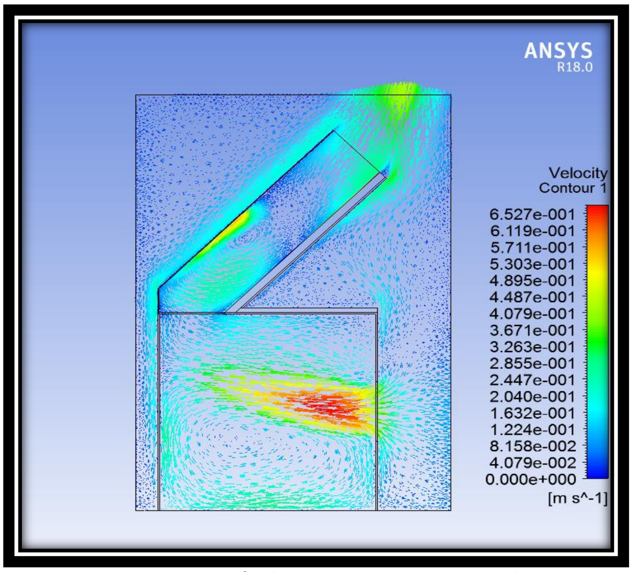


Figure 18: Contour of velocity at 10 am in southern chimney

Figure (19 and 20) describes the thermal performance of solar chimney inclination 60o.In this figure notice an increase in the rate of ventilation in the chimney in south direction starts gradually from 8 am with the increase of the solar intensity and direction until it reaches the maximum value at 10 am because of the orthogonal solar radiation with absorber leads to heating the air inside the solar channel and this cause to airflow to significantly higher. After this time the ventilation rate gradually decreases until 18 pm because of the change in the direction of solar radiation falling on the absorbent. In addition, the low solar intensity after the hour 14 pm.

Also, if the solar chimney in the west direction the ventilation rate is acceptable at the hour 8 and 10 am due to entry of some solar radiation through the window that are in the direction of the east lead to high air temperature in the room and thus increase ventilation. The maximum value of ACH is at 14 pm and then is decreased.

Figure (20) shows the contour of the velocity in the southern chimney at 10 am at which the highest occurs the ventilation rate.

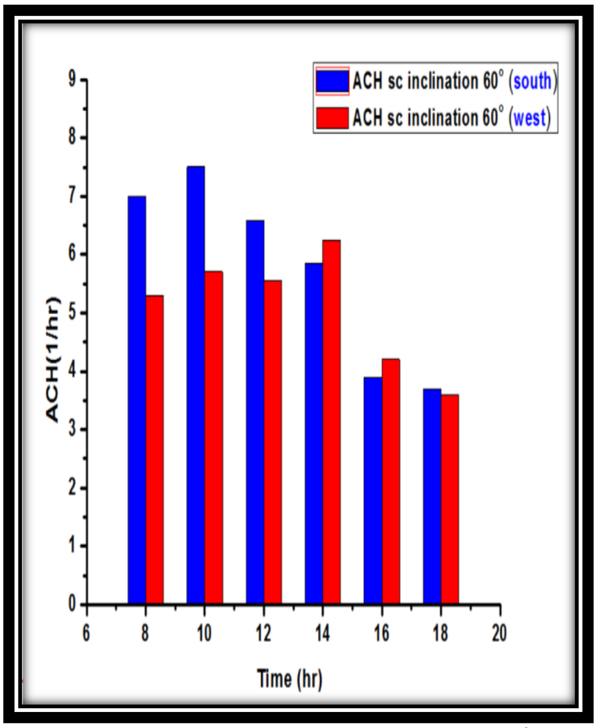


Figure 19: ACH of roof solar chimney inclination 60°

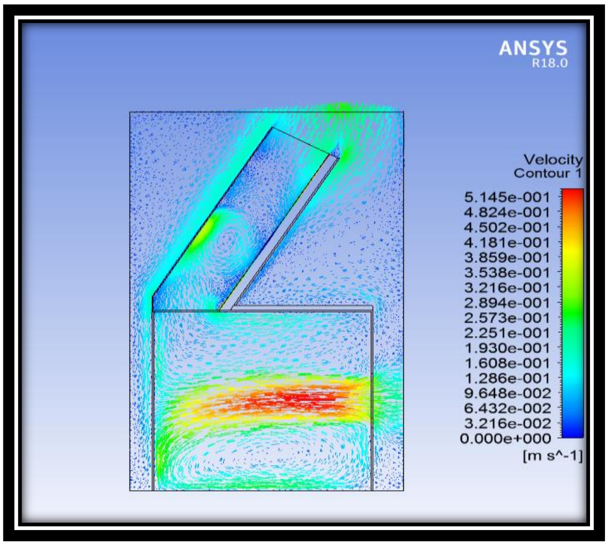


Figure 20: Contour of velocity at 10 am in southern chimney

5.1.2 Effect Solar Intensity and Solar Chimney Direction on Average Room Temperature

Figure (21) shows that the average temperature in the room is increased with the increase of the solar intensity and the ambient temperature for solar chimney inclined 30°. The average temperature in the room is reaches the maximum value (321.12 K)in south direction and (320 K) in west direction at 14 pm due to increased solar intensity and ambient temperature after this time begins to decrease gradually. Figure (22) shows the contour of the temperature in the southern chimney at 14 pm at which the highest occurs the ventilation rate.

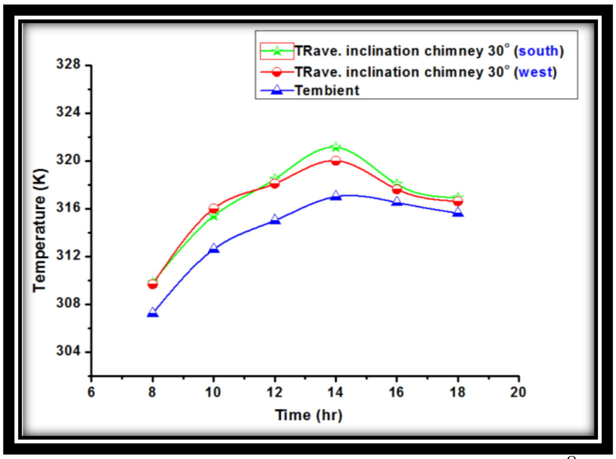


Figure 21: Compared TRave. With solar chimney inclination 30^{O}(south and west)

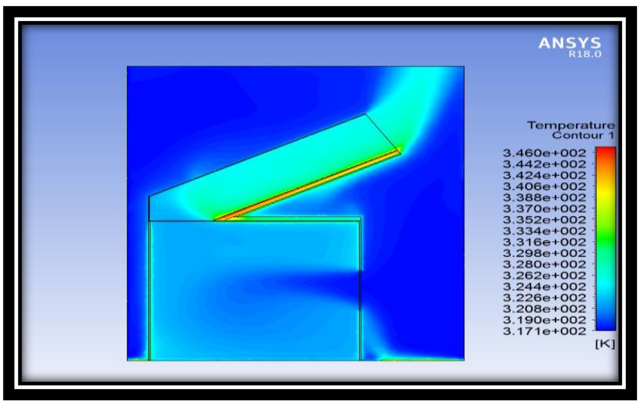


Figure 22: Contour of temperature at 14 pm the southern chimney with angle of 30°

Figure (23) shows the solar chimney behavior with inclined 45°. The average temperature in the room is increases, according to the solar intensity and the ambient temperature. The maximum value of average temperature is (٣17 k) in south direction and (320.32 K) in west direction at 14 pm due to increased solar intensity and ambient temperature after this time is gradually decreasing. Figure (24) shows the contour of the temperature in the southern chimney at 10 am at which the highest occurs the ventilation rate.

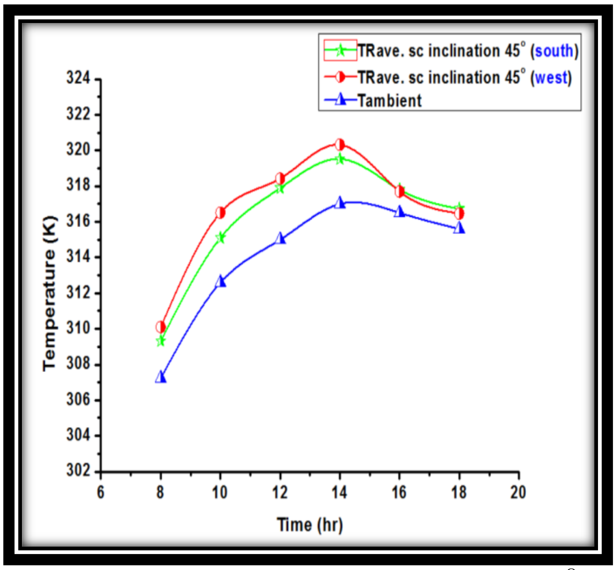


Figure 23: Compared TRave. with solar chimney inclination 45°(south and west)

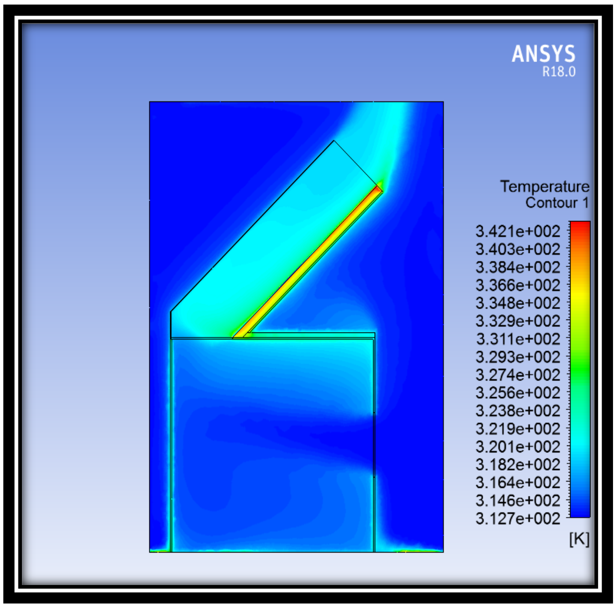


Figure 24: Contour of temperature at 10 pm in the southern chimney

Figure (25) shows that the average temperature in the room increases with the increase of the solar intensity and the ambient temperature at solar chimney inclined is 60.Temperature average inside reaches the maximum value (319.84 K) in south direction and (319.57 K) in the west direction at 14 pm due to increased solar intensity radiation and ambient temperature. In addition, to the amount of heat transferred through the walls to the room after this time begins to decrease gradually. Figure 14, 16 and 18 have the same behavior. Figure(26) shows the contour of the temperature in the southern chimney at 10 am at which the highest occurs the ventilation rate.

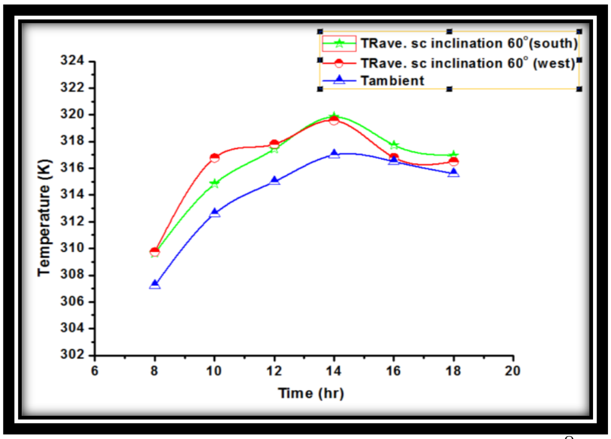


Figure 25: Compared TRave. with solar chimney inclination 60°(south and west)

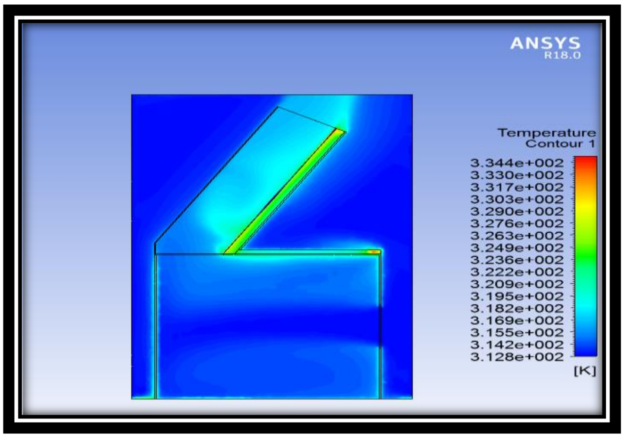


Figure.26: Contour of temperature at 10 pm in the southern chimney

5.1.3. Effect the Angle of Solar Chimney on Ach

Figure 27 and 28 is showing the effect of solar chimney angle on the ventilation rate. From the results obtained from different cases of the roof solar chimney conclude that the solar chimney at angle 45° gives the best total ACH under the climatic conditions of the city of Kut for the day (15-6-2016) as shown in the Table (4).

Table 4: best angle of inclination for solar chimney

n	Model	Average ACH south direction	Average ACH west direction	ACH total
1	Solar chimney 30°	5.63	5.64	11.27
2	Solar chimney 45°	5.6	5.75	11.36
3	Solar chimney 60°	5.45	5.1	10.55

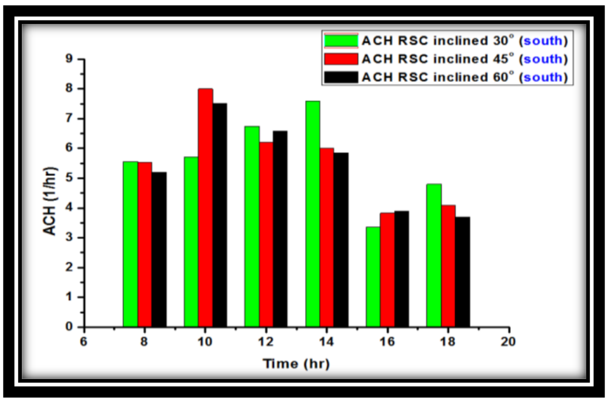


Figure 27: Comparison ACH to solar chimney at a different angle (south)

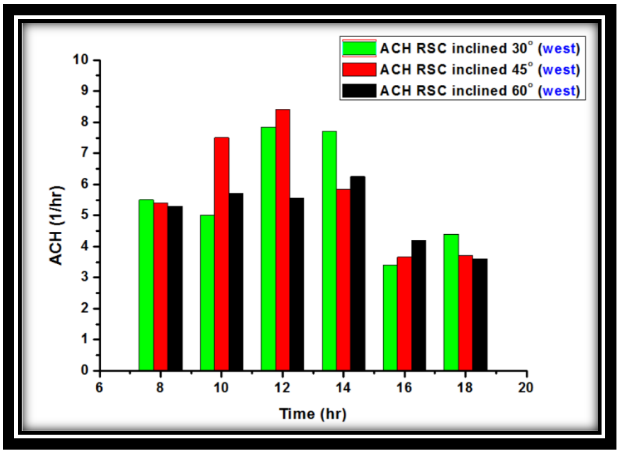


Figure.28:.Comparison ACH to solar chimney at a different angle (west)

5.2 The Second Study Case (Or Second Model)

The second model includes the effect of solar intensity, the direction of the two solar chimneys on ventilation rate and average temperature of the room.

5.2.1. Effect Solar Intensity and Solar Chimney Direction on ACH

Figure (29) shows that the model developer used two solar chimney inclination 45^o (chimney to the south and the other to the west) has the possibility to provide greater ventilation rates compared to one solar chimney.

Ventilation rate increases gradually and reaches maximum at 12 noon due to the fall of orthogonal rays on the solar chimneys leads to heating the air inside the solar channel and this cause increase in effect buoyancy force . At 16 pm amount of solar radiation incident on the chimney in the western chimney is greater than the southern chimney. The reason for this is due to the fact that the chimney variation area of the west in the developed model is (0.4 m^2) compared with the area of the solar chimney in the first case (1m^2) due to the difficulty of the design, this leads to equal the ventilation rate for both cases. At 18 pm shows the solar chimney effect western direction only and because of this small area compared of one solar chimney, this leads to lower ventilation rate. The use of two a tilted solar chimney with an angle of 45^o instead of one a tilted solar chimneys increases the ventilation rate by 31.9 %. Figure(30) illustrates contour of velocity at 12 pm for southern and western solar chimneys.

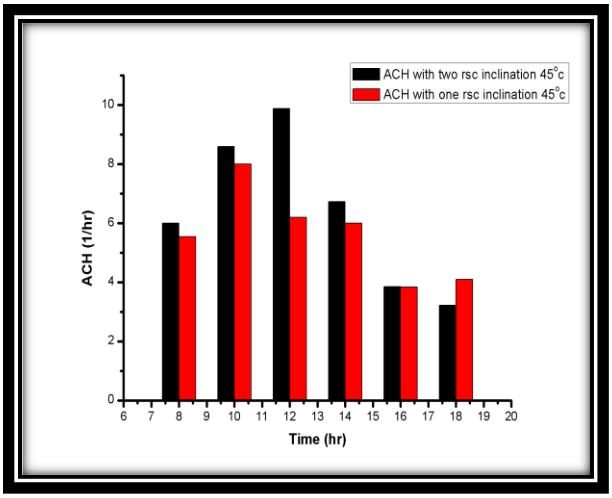
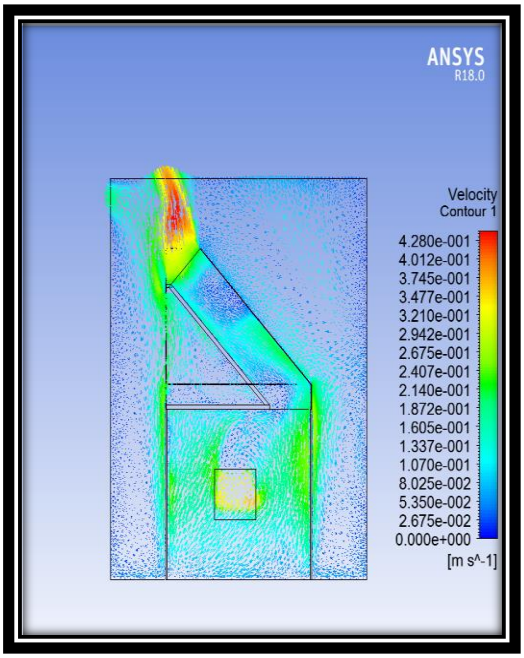
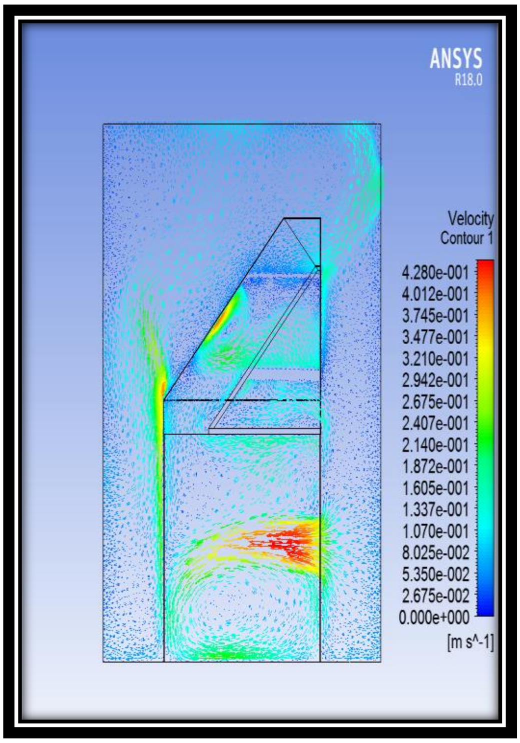


Figure.29: Comared ACH two roof solar inclination 45^{o}and one roof solar inclination 45^o



(a) South direction



(b)West direction

Figure.30: Contour of velocity at 12 pm (a) and (b)

5.2.2 Effect Solar Intensity and Solar Chimney Direction on Average Room Temperature

Figure (31) Illustrates the effect of two chimneys on average room temperature. This model provides good average temperatures in the room due to increased ventilation rates and thus provides appropriate thermal conditions for occupants of the place.

Figure(32) shows the contour of the temperature in the southern chimney at ١٢ pm at which the highest occurs the ventilation rate .The use of two a tilted solar chimneys with an angle of 45^o instead of one a tilted solar chimney reduction average room temperature to (1.34) ^{o}C.

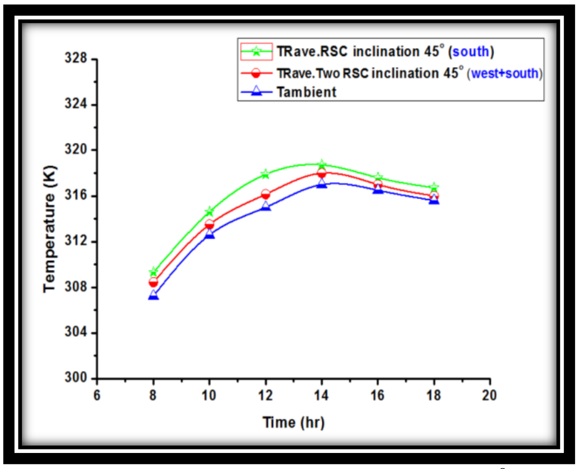


Figure 31: Affect the two solar chimneys with area 0.8 m^2 (south and west) on TRave.

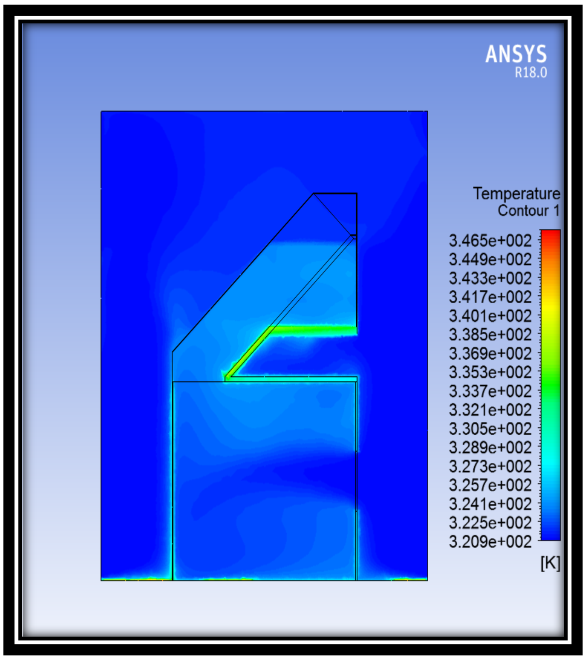


Figure.32: Contour of temperature at 12 pm in the southern chimney

6. Conclusions

• The results obtained are consistent with previously published results and this gives an opportunity to predict the thermal performance of the system.
• Considered the work of solar chimneys under the climatic conditions in Iraq is successful in providing appropriate ventilation rates due to the amount of radiation falling (2000-27500) kWh/m^2.
• The possibility of designing more than one chimney for the same building and in different directions for the purpose of increasing the rate of natural ventilation and improve the thermal conditions of the occupants of the building.
• The use of two a tilted solar chimneys with an angle of 45^o instead of one a tilted solar chimney increases the ventilation rate by 31.9 % with reduction average temperature to (1.34) ^{o}C.
• When designing buildings by depending on natural ventilation, consideration must be given to the amount of solar radiation and direction.
•Air change per hour (ACH) 4 is a value is appropriate for occupants of the place while obtained ACH more than (5) for the single solar chimney and ACH 10 Almost for a model containing two solar chimney.

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Nomenclature

RSC the roof solar chimney
ACH air change per hour (1/hr)
CFD computational fluid dynamic
ρ Air density (kg/m^3)
Cp Specific heat (J/kg .^{o}c)
K Thermal conductivity (W/m. ^{o}c)
μ Dynamic viscosity(kg/m. sec)
τ Transmissivity
α Absorptivity
ε Emissivity