Heating Performance Enhancement of a New Design Trombe Wall Using Rectangular Thermal Fin Arrays: An Experimental Approach

Mehran Rabani[a,*], Mehrdad Rabani[b]

[a] *Department of Mechanical Engineering, Faculty of Engineering, Ardakan University, P.O. Box 184, Ardakan, Iran, m.rabani@ardakan.ac.ir*

[b] *Department of Civil Engineering and Energy Technology, OsloMet – Oslo Metropolitan University, Norway, mehrab@oslomet.no*

[b] *Department of Energy and Process Engineering, Norwegian University of Science and Technology, Norway, mehrdadr@stud.ntnu.no*

[*] *Corresponding author: Assistant Professor, E-mail address: m.rabani@ardakan.ac.ir*

Abstract

It has been nowadays recognized that addressing energy use in buildings can reduce the fossil fuels usage and CO_2 emission. Trombe wall is a widely applicable passive solar design option that can significantly reduce the fossil fuel consumption in buildings. This paper experimentally dealt with the effect of applying vertical thermal fin on the absorber of Trombe wall with new design. Three types of aluminum, brass and copper fins were investigated. The experiments were carried out at arid climate of Yazd, Iran. The results showed that when the thermal fin is used the performance efficiency of the Trombe wall increases up to 3% in terms of stored energy within the Trombe wall and 6% in terms of natural convection heat transfer rate inside the channel. However, adopting more thermal fins on the absorber could not ensure higher heating efficiency in terms of stored energy for all cases. Furthermore, copper fin led to maximum heating efficiency and highest average room temperature among three fin types.

Keywords: Trombe Wall, Thermal fin, Stored energy

Nomenclature

A_{abs}	absorber area (m^2)
A_c	channel area (m^2)
c	specific heat of concrete (J/kg.K)
E	energy term (J)
g	acceleration due to gravity (m/s^2)
H	Trombe wall height (m)
Pr	Prandtl number
Ra	Rayleigh number
m_c	mass of concrete (kg)
$\dot{m}$	mass flow rate (kg/s)
$\overline{Nu}$	average Nusselt number
q_{abs}	heat gained by the absorber (W/m^2)
T	temperature (°C)
T_{avg}	average temperature of the Trombe wall (°C)
T_{down}	average air temperature of the down vent of Trombe wall (°C)
T_{up}	average air temperature of the up vent of Trombe wall (°C)
t	time (s)
Ꝟ	volume of concrete (m^3)
V_a	air velocity in the channel (m/s)
Greek symbols	
α	Thermal diffusivity (m^2/s)
β	Thermal expansion coefficient (1/K)
ρ	air density (kg/m^3)
ρ_c	concrete density (kg/m^3)
η_c	heating efficiency of the system in accordance with the natural convection heat transfer
η_s	heating efficiency of the system in accordance with the stored energy
ν	Kinematic viscosity (m^2/s)

1. Introduction

Buildings energy use accounts for nearly 25% of the total use of delivered energy throughout the world [1], and it is expected that the building energy use will increase by around 48% from 2010 to 2040 [2]. During last few decades, passive solar technologies have drawn enlarging research interests due to increasing energy use by residential and commercial buildings [3]. The functionality of this technology is especially important in cities with very hot and dry climate such as Yazd (Iran), characterized with dry and cold winters (Fig. 1). Trombe wall offers an excellent performance in this regard. It can meet the thermal comfort requirements in buildings while reducing the building energy use in low to medium latitude countries.

Due to the fact that the Trombe wall system was originally conceived for cold climates, there is a large body of research studying its winter performance [4-11]. These researches commonly dealt with the Trombe wall performance with 20 cm thickness of concrete wall.

Fernández-González [12] in Midwestern and Eastern Temperate Climate Zone with average outdoor temperature 10.4°C, Okonkwo and Akubuo [13] in dry and rainy seasons of Nigeria with average outdoor temperature 18°C, and Chen et al. [14] in the north semi-humid temperature district with average outdoor temperature around -6°C evaluated the Trombe wall heating performance in residential buildings. Their results revealed that a 20 cm layer of concrete wall provides desirable indoor air temperature around 25 °C.

Fig. 1. A traditional building designed to receive the highest amount of solar energy in Yazd in winter.

Many researches were carried out to improve the thermal performance of Trombe wall such as enhancing the coating absorptivity of the Trombe wall and using different insulation levels of the room [15], adopting semi-transparent photovoltaic thermal-Trombe wall [16] and integrating phase change materials (PCM) with Trombe wall [17].

Thermal fin is another device that can improve the performance of Trombe wall. Zhang and Liu [18] investigated the optimum geometric arrangement of vertical rectangular fin arrays in natural convection. It was found that the theoretical expression of the optimal spacing between the plates was obtained by the natural convection boundary layer theory. Furthermore, the results revealed that the optimal spacing was 4/3δ (δ is the thickness in the velocity fields of the boundary layer), where a significant heat transfer increase was resulted by the temperature coordination and the velocity superposition.

Ahmadi et al. [19] investigated the natural convection heat transfer of rectangular interrupted fins. The results indicated that adding interruptions to vertically mounted rectangular fins could enhance the thermal performance significantly. Nevertheless, the results suggested that there is an optimum fin interruption.

Lieto Vollaro et al. [20] investigated the optimum design of vertical rectangular fin arrays. The optimum performance of the system was examined by taking into account the effect of thermal conductivity and emissivity of the fin materials as well as the heat exchanged by the finless portion of the base plate. The results suggested that the main influence of fin conductivity was reduction of the optimal fins spacing, which could increase the heat flux by 20%.

Nada [21] studied natural convection heat transfer in a horizontal and a vertical closed narrow enclosure with heated rectangular finned base plate. The results suggested an optimum fin spacing for which Nusselt number (Nu) and finned surface effectiveness (ε) were maximum. It was observed that: (1) by increasing the fin length, the both ε and Nu increase; (2) by increasing Rayleigh number (Ra), Nu_H increases for any fin-array geometry; and (3) for any fin-array geometry, at $Ra > 10000$, increase of Ra would decrease ε while for fin-array geometries of large fin spacing, at $Ra < 10000$, increase of Ra would increase ε.

Hosseini et al. [22] carried out a numerical study on the rectangular fin geometry effect on the solar chimney performance. The effect of using discontinuous fins in the solar chimney with different interruption gaps were examined. The results revealed that the discontinuous fins could either improve or diminish the solar chimney performance.

So far, several numerical and experimental studies have been carried out on the Trombe wall performance equipped with thermal fins. However, the present study has focused on the heating application of the Trombe wall with new design, which was developed by Rabani et al. [23, 24], integrated with vertical thermal fins. Three different fin types and numbers have been used to evaluate the contributions of the thermal fin to the heating efficiency of the system in terms of natural convection heat transfer inside the channel as well as the stored energy within the Trombe wall.

2. Experimental setup

The case study is an experimental test room equipped with passive solar Trombe wall system with interior dimensions of 3m×2m×3m in Yazd, Iran. Also, regarding the envelop conditions, 14 cm foam along with 5 cm covering for both inner and outer surface of the test room walls with a mixture of thatch and concrete, which is a suitable thermal insulating material has been used [23, 24]. In addition, the material type in the wall of the room, all optimum dimensions, and the type of sensors are based on the pervious experimental work [23, 24] (Fig. 2). Detail information about the sensor uncertainty could be found in the previous work [23]. As Fig. 2 shows, the Trombe wall was faced towards South and was also located in the southern part of the test room.

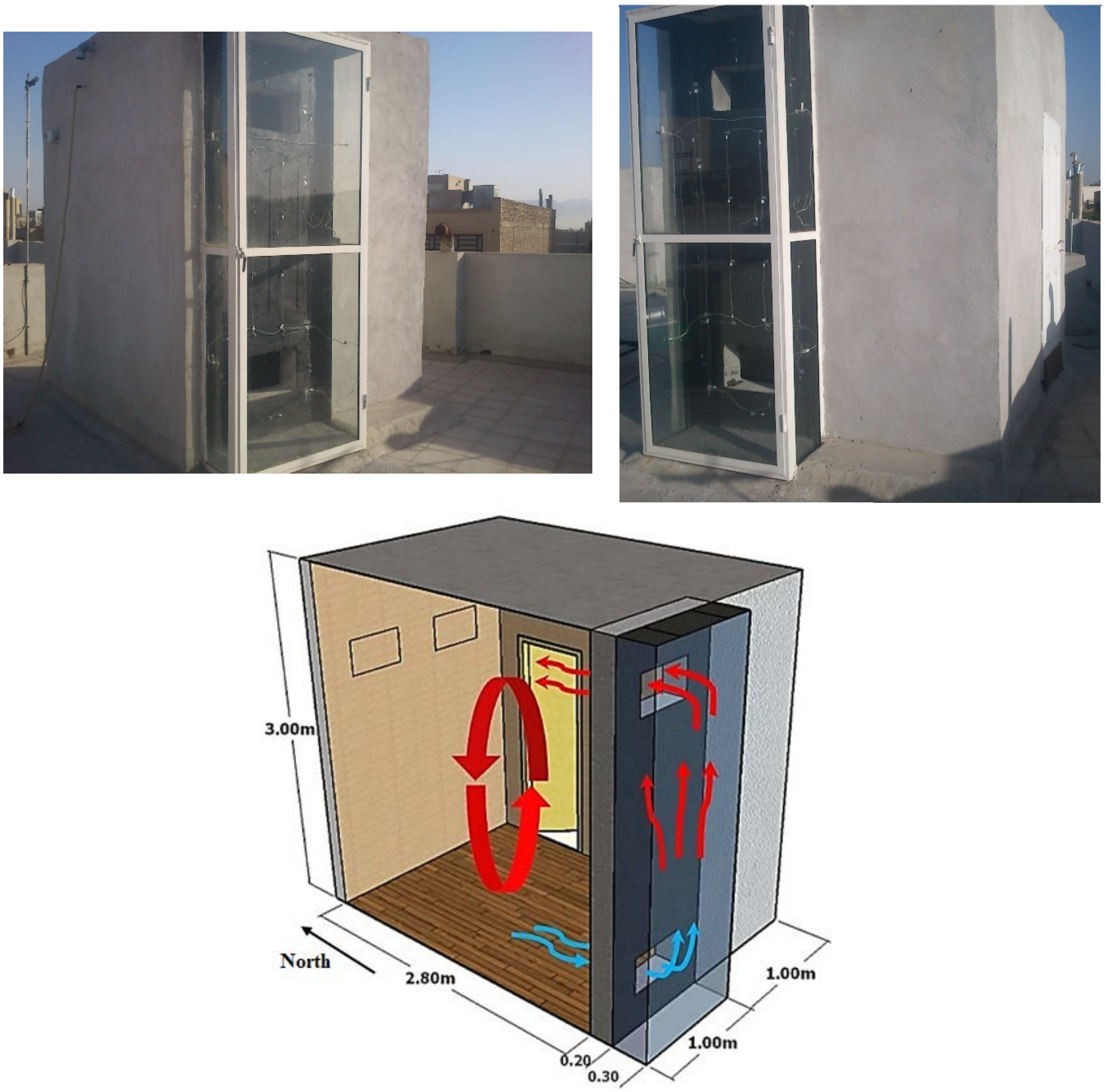
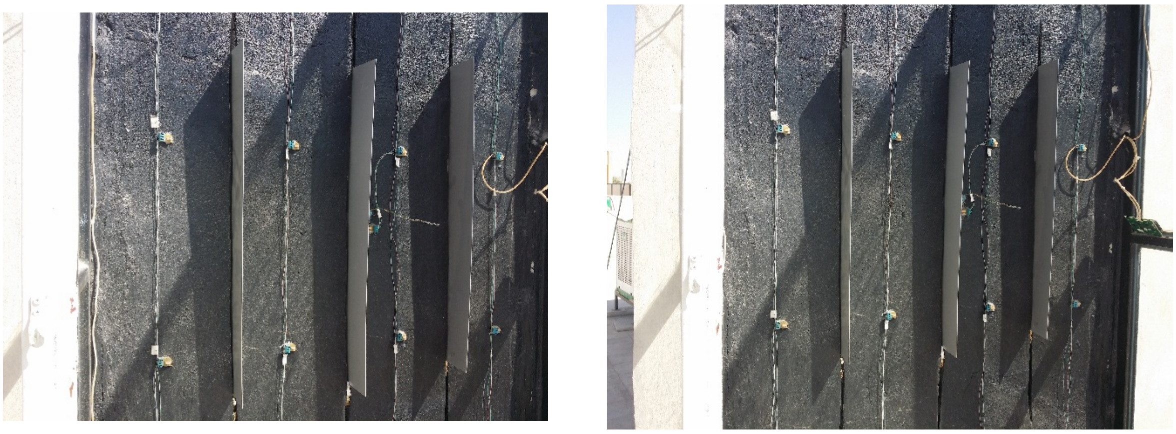


Fig. 2. The new designed Trombe wall and experimental room [23, 24]

Generally, thermal fin is defined as the surface employed for enhancing the convection heat transfer rate. In the present study, three fin types of brass, aluminum, and copper have been employed (Fig. 3). Table 1 represents the properties of three fin types. The fins were positioned vertically into the parallel grooves on the absorber of the Trombe wall (Fig. 3).

The grooves had 2-3 cm depth and the thickness resembled that of fin. As it can be seen from Table 1, width of each fin is 10 cm that with regard to the depth of the grooves on Trombe wall (2-3 cm), when the fin is embedded in the groove, only 7 to 8 cm of the fins is projected on the absorber. In order to avoid the effect of fin shadows on each other as well as to have a same distance between the fins, the optimal distance was considered to be 30 cm (Fig. 4). Only the frame of Trombe wall channel may cast a shadow on the fins and the absorber, which is inevitable. However, it only happens for a short period. In addition, the new design of Trombe wall channel caused the all fins to be exposed to the sun during the daytime. Furthermore, in order to properly fix the fins in the grooves, a temporary yellow bullet-shape glue was used in the bottom part of the grooves, below fins.

(a)



(b)

(c)

Fig. 3. Implementation of thermal fin on the Trombe wall absorber (a) Brass fin, (b) Aluminum fin and (c) Copper fin

Table 1. Thermal fin properties

Type	Density(Kg/m^3)	Dimensions	Thermal conductivity(W/m.K)
Brass	8530	10×100Cm^2×1mm	110
Aluminum	2702	10×100Cm^2×1mm	237
Copper	8933	10×100Cm^2×1mm	401

Fig. 4. The conditions of fixing and spacing of thermal fins

3. Results

The effect of fin numbers and type of them on the heating performance of the Trombe wall system was studied. The results included temperature distribution in different room points, Rayleigh number and distribution of convection heat transfer coefficient, stored energy variation, the rate of air velocity, and the heating efficiency variation for two months of January and February 2018.

3.1. Fin type effect

Accurate analysis of fin type effect on the heating performance of the Trombe wall system necessitates a similar outdoor condition for several consecutive days. As it is evident in Table 2, the outdoor conditions for these consecutive days are almost the same.

Table 2. Outdoor conditions for four consecutive days

Day- Fin type	Outdoor temperature (°C)	Average solar heat flux received by absorber (W/m^3)
1 February - Without fin	14	382
2 February - Brass fin	13.8	381.5
3 February - Aluminum fin	14.1	381
6 February - Copper fin	14	380.1

Figs. 5 to 7 indicate the temperature distribution on the absorber, backside of the Trombe wall, room space and the channel space. Adopting thermal fins on the Trombe wall absorber has increased the absorber temperature by midday due to solar heat flux increase and conduction heat transfer through the fins into the wall. From midday onwards, increase of natural convection heat transfer from the absorber to the channel has reduced the absorber temperature. In addition, the brass fin led the absorber temperature to increase at midday, however, due to its lower conduction heat transfer coefficient compared to two other fin types, less temperature decrease was observed in the late hours of the day. Owing to high conductivity of the copper fin, compared to two other fin types, the absorber experienced higher temperature increase and decrease at midday and late hours of the day respectively. In other words, the higher the thermal fin conductivity, the higher the extremes at midday and late hours of the day.

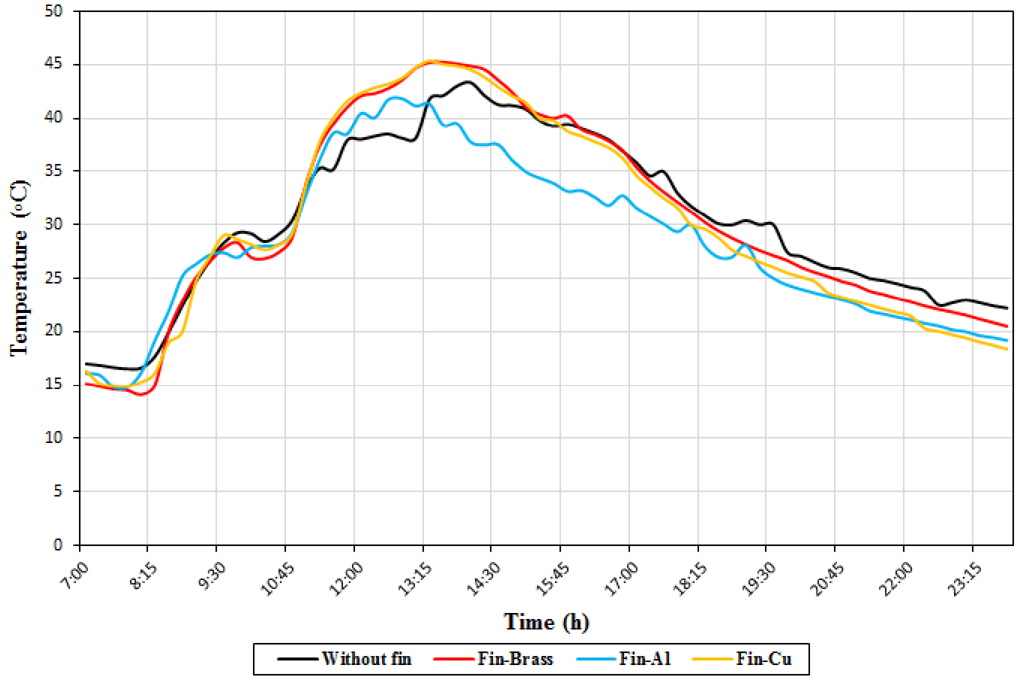


Fig. 5. Variation of absorber temperature for different fin types

It is worth mentioning that in the early hours of the day, the thermal fin has operated conversely and has caused the temperature of the backside of the Trombe wall to decrease (Fig. 6), which has subsequently caused the room space temperature to decrease (Fig. 7). The reason is the combined effect of conduction heat transfer through the absorber to the fin and the natural convection heat transfer from the fin to the channel space. This phenomenon has faded as time elapsed and the temperature of the fin has increased.

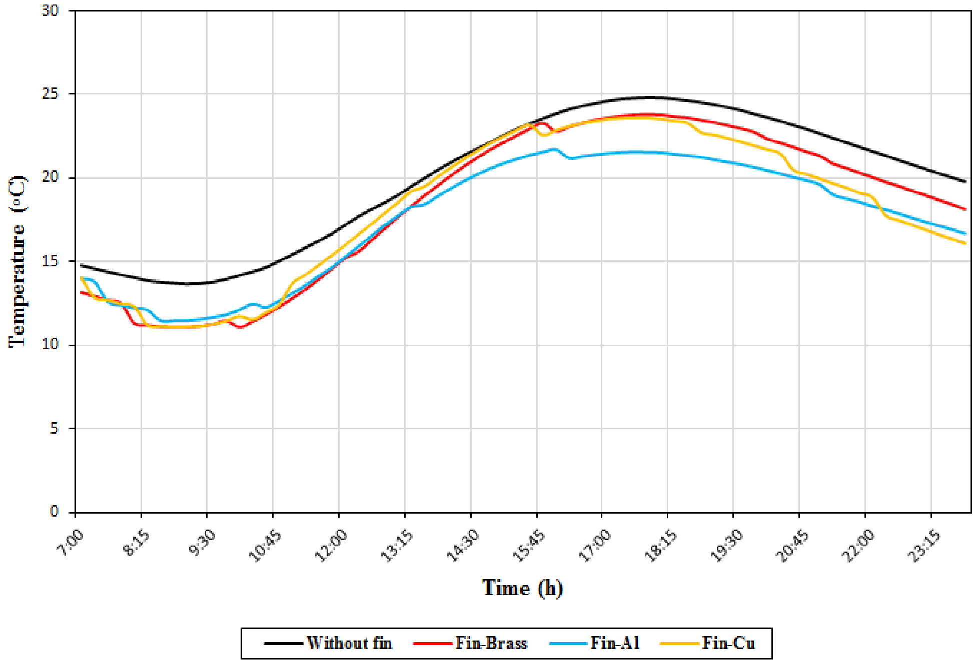


Fig. 6. Temperature variation of Trombe wall backside for different fin types

Figs 7a-7d represent the temperature distribution at different sections of the Trombe wall systems. The advantage of using thermal fin in the daytime was the enhancement of natural convection heat transfer within the channel space; thereby increase of airflow recirculation through the air vents of Trombe and inside the room in comparison with the Trombe wall without thermal fins. The higher the thermal conductivity, the higher the natural convection and temperature increment in these sections.

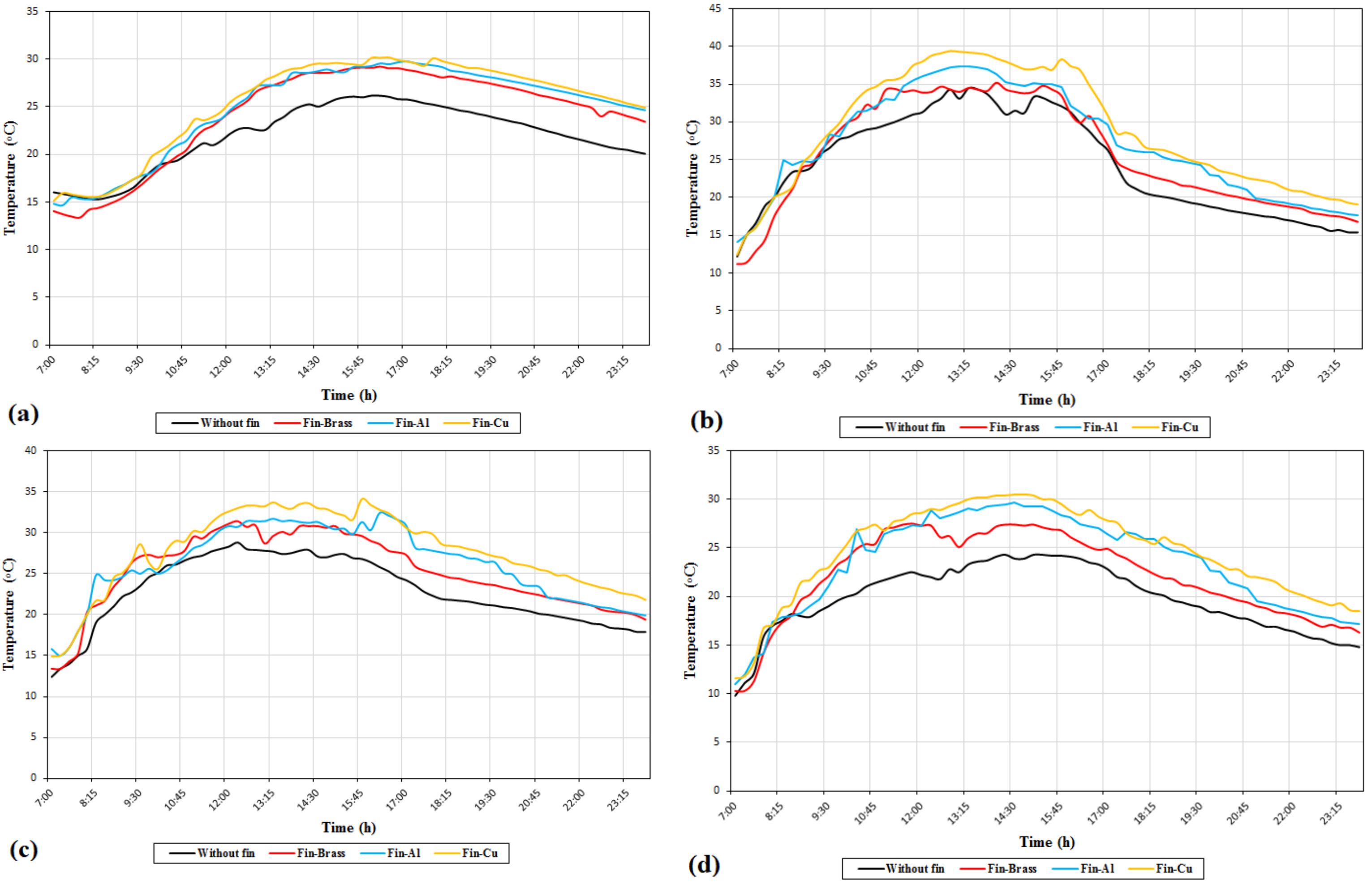


Fig. 7. Variation of temperature for different fin types for (a) room space, (b) channel space, (c) upper vent and (d) lower vent

As it is evident form the Fig. 8, applying thermal fin on the Trombe wall absorber has enhanced the convection heat transfer rate and the airflow velocity inside the channel. According to the thermal conductivity of thermal fins, the average airflow velocity of Trombe wall without fin, with the brass, aluminum, and copper fins are 0.056 m/s, 0.057 m/s, 0.06 m/s, and 0.063 m/s respectively. The low thermal conductivity of brass fin has led to low discrepancy of airflow velocity between the Trombe wall without fin and with brass fin.

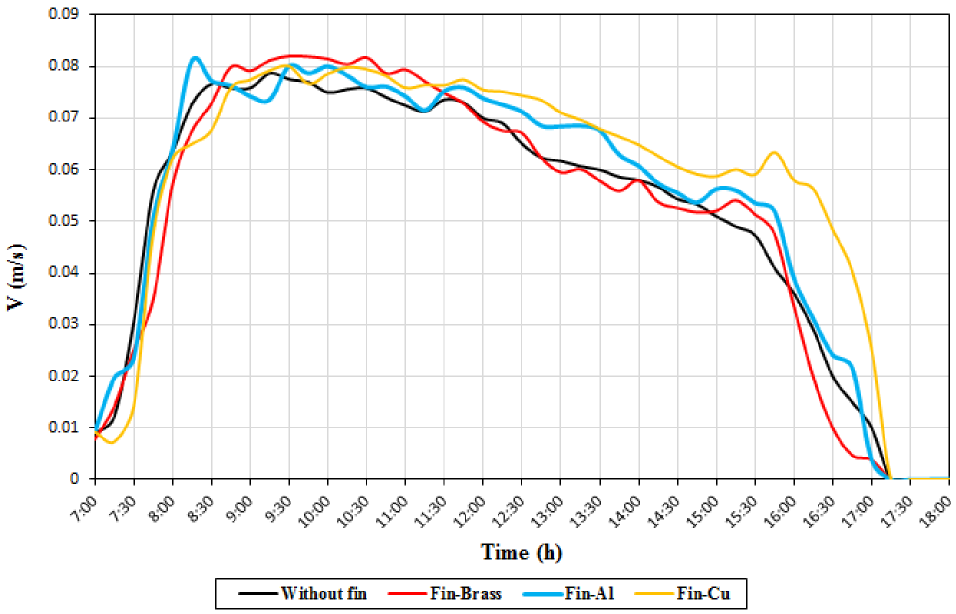


Fig. 8. Variation of airflow velocity inside the channel for different fin types

Fig. 9 illustrates the hourly average stored energy within the Trombe wall, defined according to Eq. 1 [23, 24]. With thermal fin, the stored energy amount has been enhanced at midday due to conduction heat transfer through the fin into the Trombe wall. However, in the late hours of the day, due to the increase of conduction heat transfer through the Trombe wall to the channel space and the increase of natural convection heat transfer inside the channel, the hourly stored energy amount decreases higher than that within the Trombe wall without thermal fin.

The aluminum fin has resulted in lower energy to be stored within the Trombe wall in comparison with the brass one at midday because of higher thermal conductivity of the aluminum type. Nevertheless, the copper fin lead to lesser decrease in the stored energy within the Trombe wall in comparison with the aluminum one due to high temperature of thermal fin at midday. In the late hours of the day, the high thermal conductivity of the copper fin adversely affected the stored energy within the Trombe wall and caused the average stored energy to be minimized.

$$\frac{\Delta E}{\Delta t} = \frac{m_c c \Delta T_{avg}}{\Delta t} = \frac{\rho_c \forall c \Delta T_{avg}}{\Delta t}, \Delta t = t_i - t_{i-1} = 1 hour \quad (1)$$

$$\Delta T_{avg} = T_{avg.i} - T_{avg.i-1} \quad (2)$$

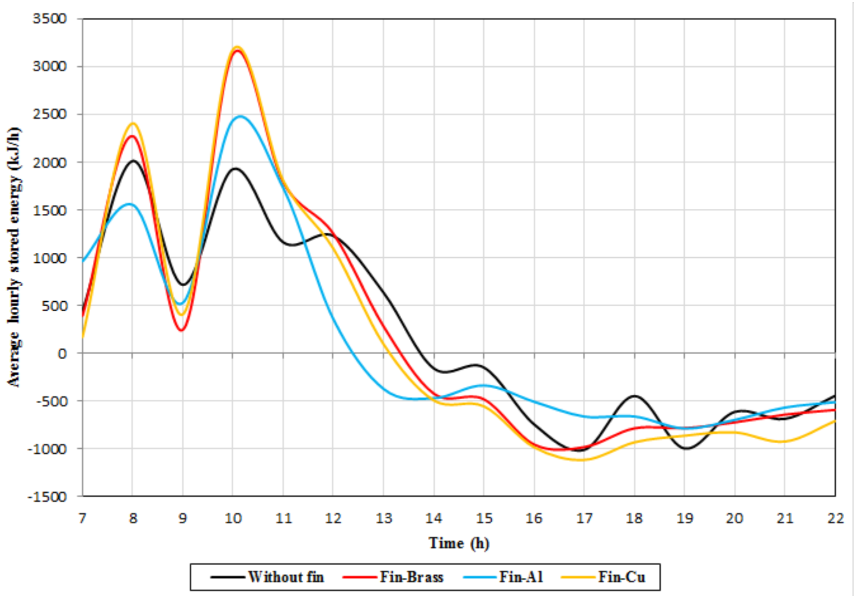


Fig. 9. Hourly average stored energy within the Trombe wall for different fin types

Figs. 10 and 11 demonstrate the variation of Rayleigh number and convective heat transfer coefficient on the Trombe wall absorber respectively. The Rayleigh number was computed according to the Eq. 3 [25-28] and the convective heat transfer coefficient of the absorber was computed based on the Eqs. 4 and 5 [25-27, 29]. With regard to the fact that utilizing thermal fin on the Trombe wall absorber increased the natural convection heat transfer in different parts of the Trombe wall system, hence the Rayleigh number and the convective heat transfer coefficient also increased. The copper fin generated higher natural convection heat transfer inside the channel due to its higher thermal conductivity in comparison with two other fin types.

$$Ra = \frac{g\beta \Delta T H^3}{\nu \alpha} \tag{3}$$

Laminar flow (4)

$$\overline{Nu_H} = 0.68 + \frac{0.67 Ra_H^{\frac{1}{4}}}{\left[1 + \left(0.492/\Pr\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}}$$

Turbulent flow (5)

$$\overline{Nu_H} = \left\{ 0.825 + \frac{0.387 Ra_H^{\frac{1}{6}}}{\left[1 + \left(0.492/\Pr\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\}^2$$

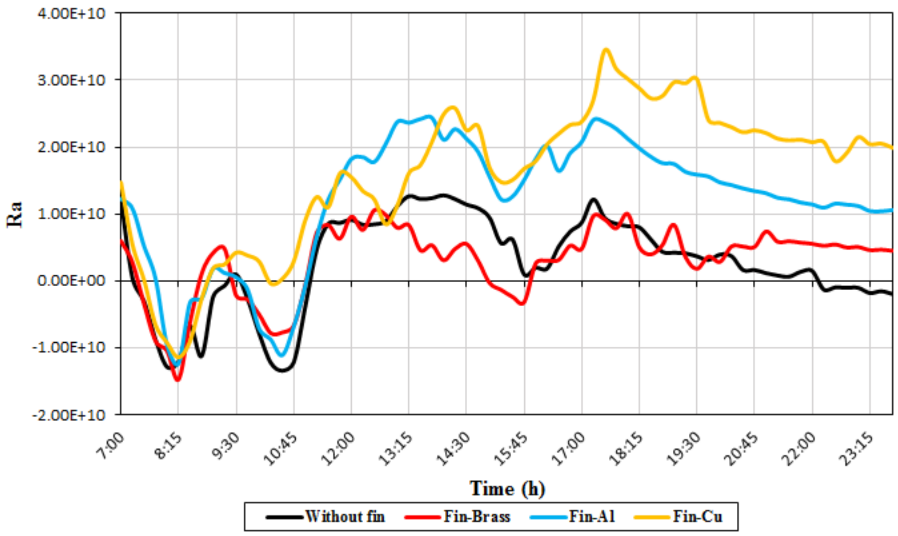


Fig. 10. Rayleigh number variation inside the channel

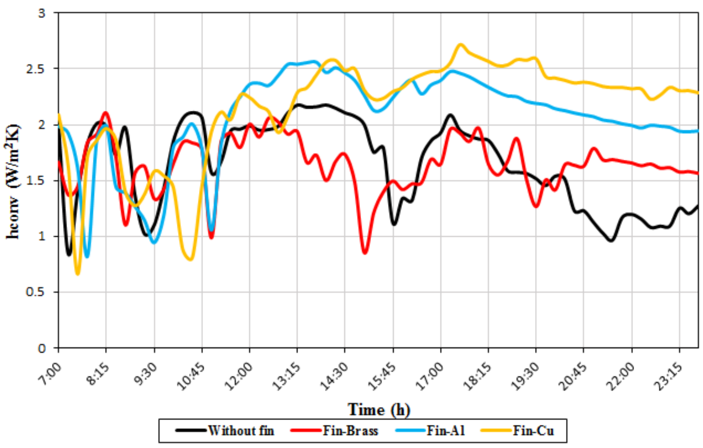


Fig. 11. Variation of convection heat transfer coefficient on the absorber

Fig. 12 indicates that the heating efficiency of the system in accordance with the stored energy, defined based on Eq. 6 [23, 24] and the natural convection heat transfer (Eq. 7) [23, 24], respectively. When the stored energy is the matter of importance, the heating efficiency of the system for the Trombe wall with brass and copper fins is higher than that with aluminum type, around 3% higher than the Trombe wall without thermal fin, due to storing higher energy amount within the Trombe wall. As the convection heat transfer is the matter of concern, the copper fin has the maximum heating efficiency of the Trombe wall system, approximately 6% higher than the Trombe wall without thermal fin, due to creating higher natural convection heat transfer inside the channel.

$$\eta_S = \frac{mc\Delta T_{avg} / \Delta t}{q_{abs} A_{abs}} \tag{6}$$

$$\eta_c = \frac{\dot{m}c(T_{up} - T_{down})}{q_{abs} A_{abs}} = \frac{\rho A_c V_a c(T_{up} - T_{down})}{q_{abs} A_{abs}} \tag{7}$$

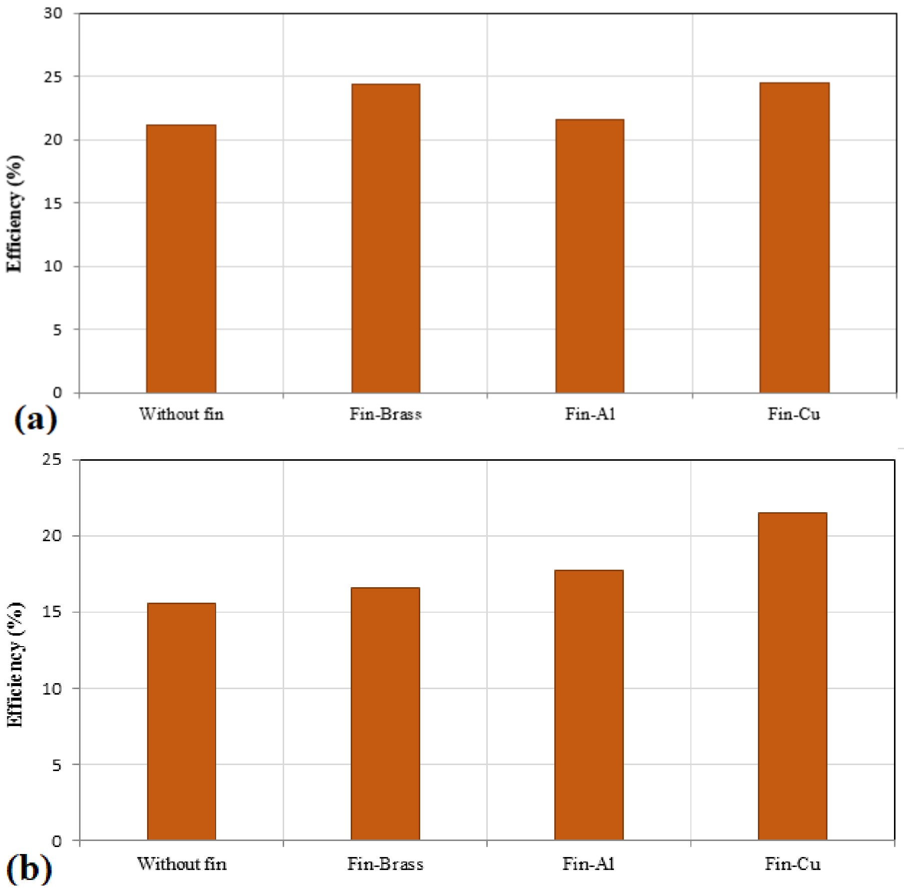


Fig. 12. Heating performance efficiency of the Trombe wall system based on the (a) stored energy, and (b) natural convection heat transfer rate

Comparing the aluminum and copper fins, both fin types produced almost similar temperature distribution inside the room space. However, regarding the heating efficiency of the system, the copper fin resulted in more desirable condition inside the room than aluminum fin.

3.2. Effect of the number of fins

Precise analysis of the effect of fin numbers on the different parameters of the Trombe wall system necessitates having a similar outdoor condition for several consecutive days. According to the Tables 3, 4, and 5, four consecutive days, considered for empirical study, had similar outdoor conditions.

Table 3. Outdoor condition for brass fin

Day- Fin numbers	Outdoor temperature (°C)	Average solar heat flux received by absorber (W/m^3)
22 January - Without fin	9	401
24 January - 2 Fins	8.5	400.6
25 January - 3 Fins	9	400.1

Table 4. Outdoor condition for aluminum fin

Day- Fin numbers	Outdoor temperature (°C)	Average solar heat flux received by absorber (W/m^3)
23 January - Without fin	11.1	400.8
26 January - 2 Fins	11	400
27 January - 3 Fins	11.7	399.7

Table 5. Outdoor condition for copper fin

Day- Fin numbers	Outdoor temperature (°C)	Average solar heat flux received by absorber (W/m^3)
11 February - Without fin	21.3	377.4
12 February - 2 Fins	21.8	377
13 February - 3 Fins	21	376.7

The trend of absorber temperature variation for each type of thermal fin is similar to that in Fig. 5. As it can be seen in Fig. 13 three aluminum and brass fins resulted in higher absorber temperature than two other ones at midday. But they posed a higher reduction of the absorber temperature at the late hours of the day. In addition, in comparison with three fins, two copper fins not only led to higher absorber temperature at midday, but also less absorber temperature reduction so that the absorber temperature in this case is even higher than the case without thermal fin in the late hours of the day.

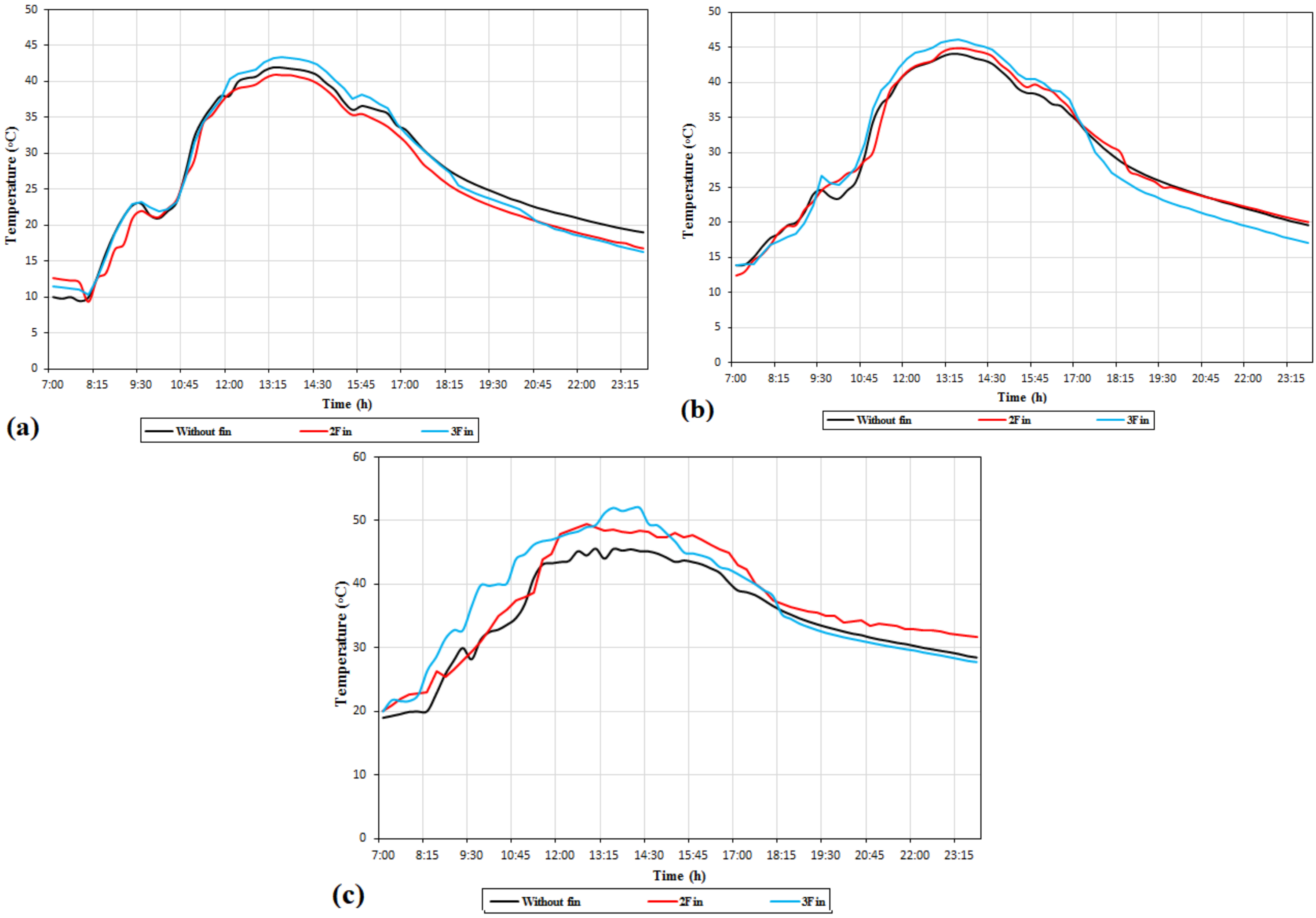


Fig. 13. Variation of absorber temperature for (a) brass, (b) Aluminum, and (c) copper fins

The trend of temperature variation of the Trombe wall backside resembled that shown in the Fig. 14. In comparison with two thermal fins, three ones resulted in higher Trombe wall backside temperature at midday and the same temperature decrease in the late hours of the day. The results of Fig. 14c also showed that whether two or three fins are used, the Trombe wall backside temperature is less than the case without thermal fin.

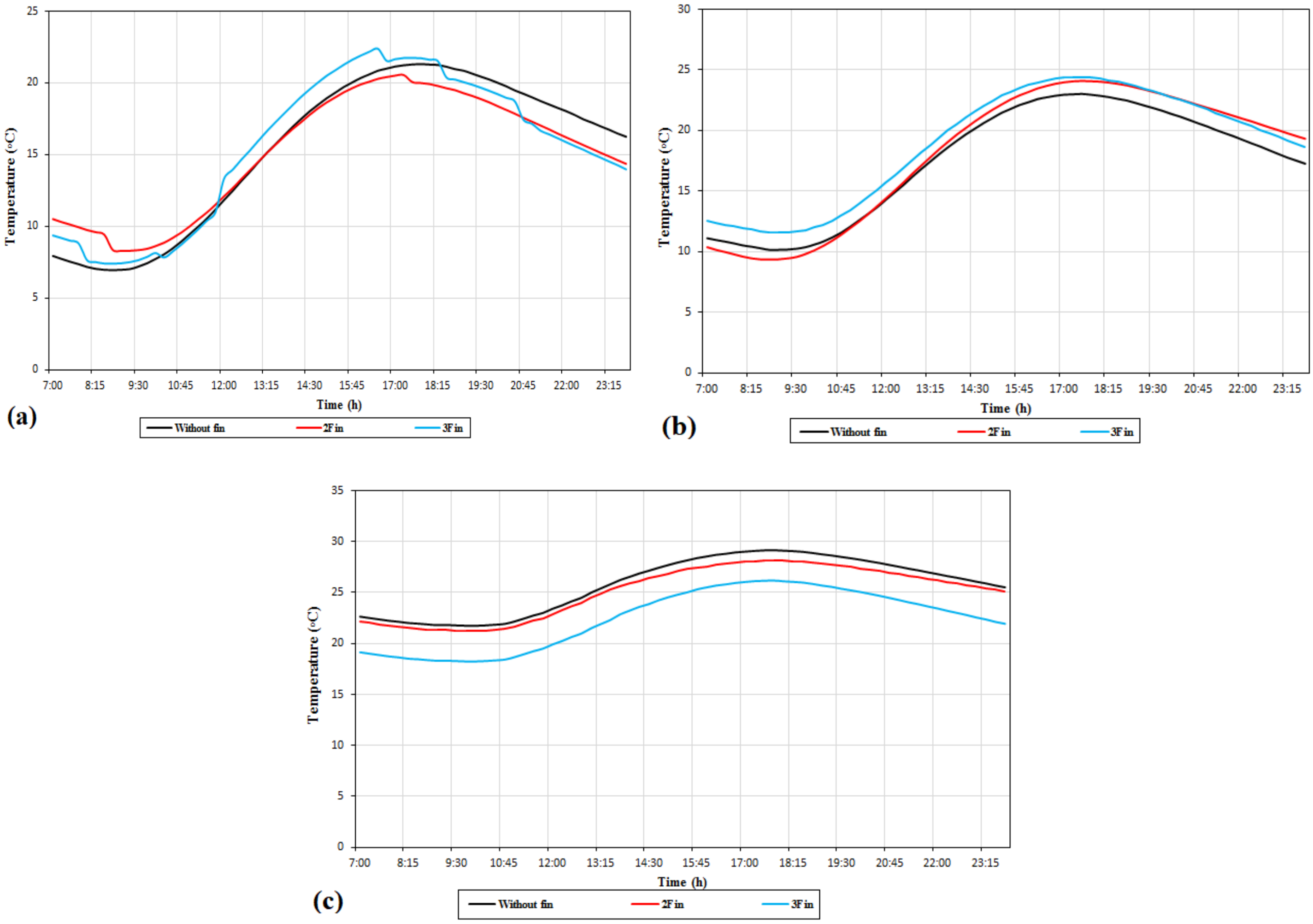


Fig. 14. Temperature variation of Trombe wall backside for (a) brass, (b) aluminum, and (c) copper fins

The temperature variations in the room and the channel (Figs. 15 and 16) are similar to that in Fig. 7. With increase of fin numbers, the natural convection heat transfer inside the channel increases which in turn causes the temperature of the room, the channel and the vents to increase.

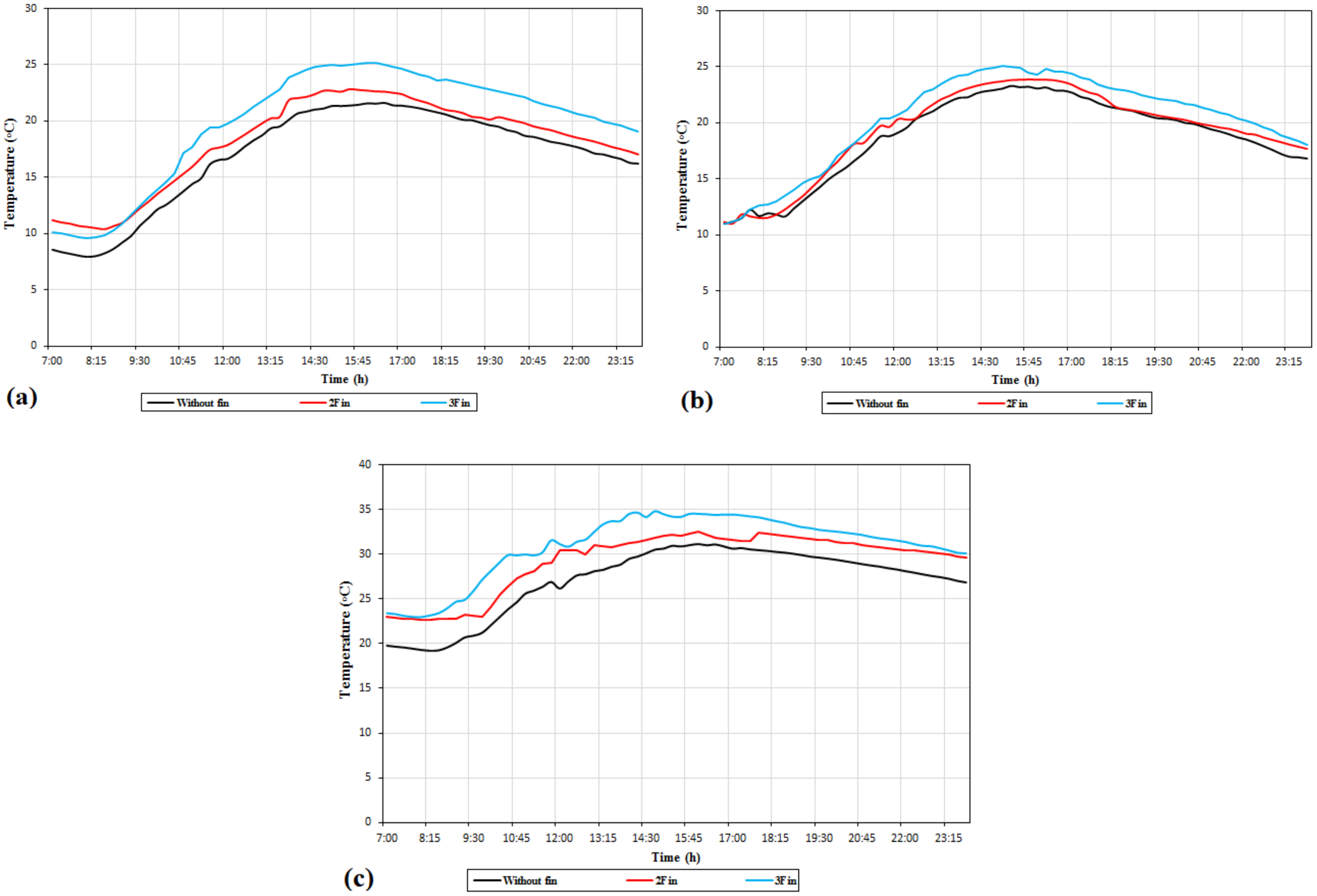


Fig. 15. Room temperature variation for (a) brass, (b) aluminum, and (c) copper fins

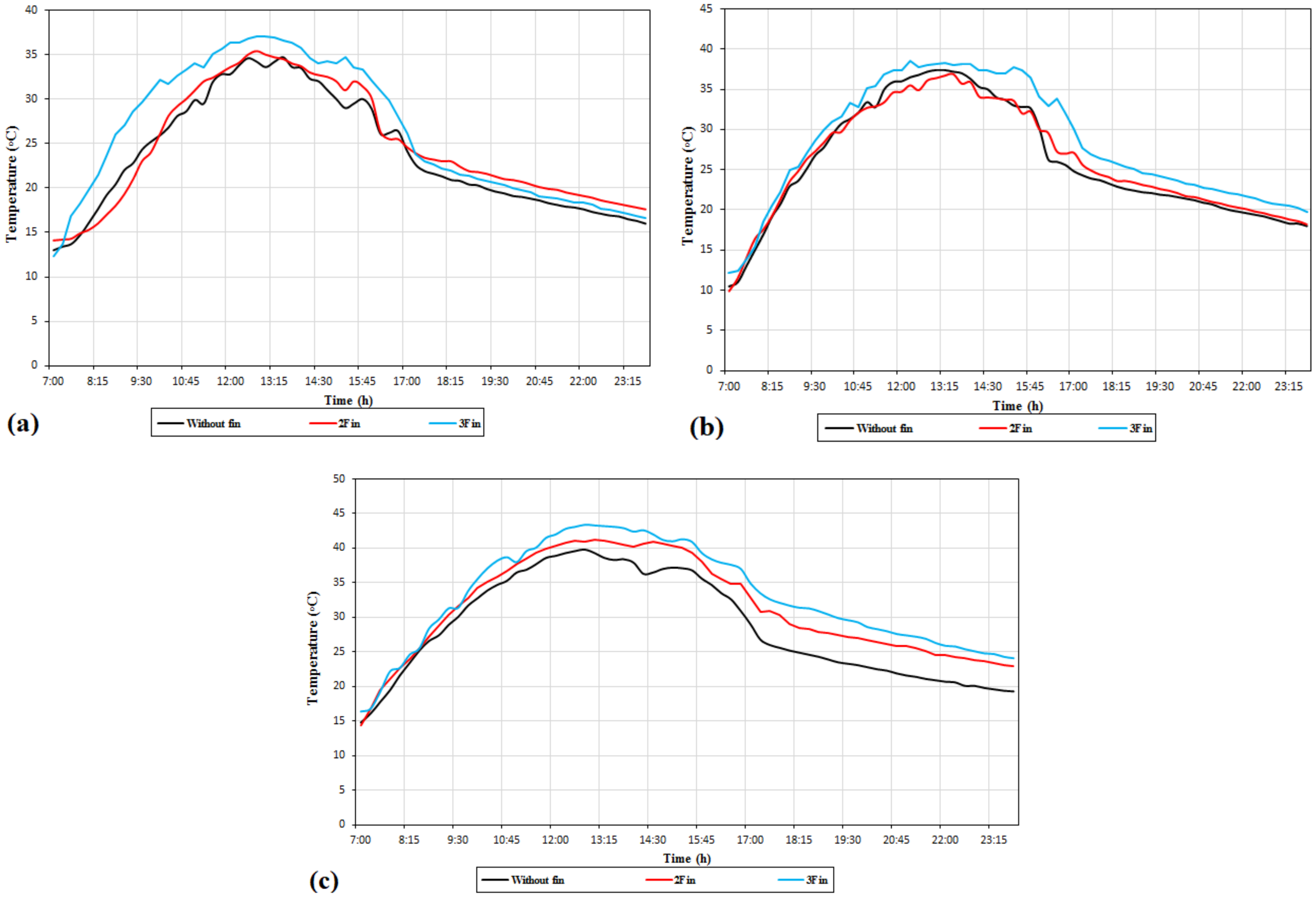


Fig. 16. Channel temperature variation for (a) brass, (b) aluminum, and (c) copper fins

Based on the velocity result, increase of thermal fin number intensifies the natural convection heat transfer rate that in turn expedites the air flow rate inside the channel. The average air flow velocity variation for different fin types has been indicated in the Table 6.

Table 6. Average velocity variation inside the channel for different number and types of thermal fin

Fin type	Without fin (m/s)	2 Fins (m/s)	3 Fins (m/s)
Brass fin	0.051	0.056	0.057
Aluminum fin	0.075	0.076	0.078
Copper fin	0.077	0.082	0.084

The variation of hourly average stored energy within the Trombe wall has been indicated in the Fig. 17. An increase in the number of brass fin increased the stored energy within the Trombe wall due to the enhancement of conduction heat transfer through the thermal fins into the Trombe wall at midday. Furthermore, two copper and aluminum fins caused more stored energy at midday because these fin types, especially copper one, had high thermal conductivity. Consequently, further increase in the number of thermal fin led to higher transferred energy from the Trombe wall to the channel. In the late hours of the day, as expected, an increase in the number of each fin type caused the hourly average stored energy within the Trombe wall to decrease.

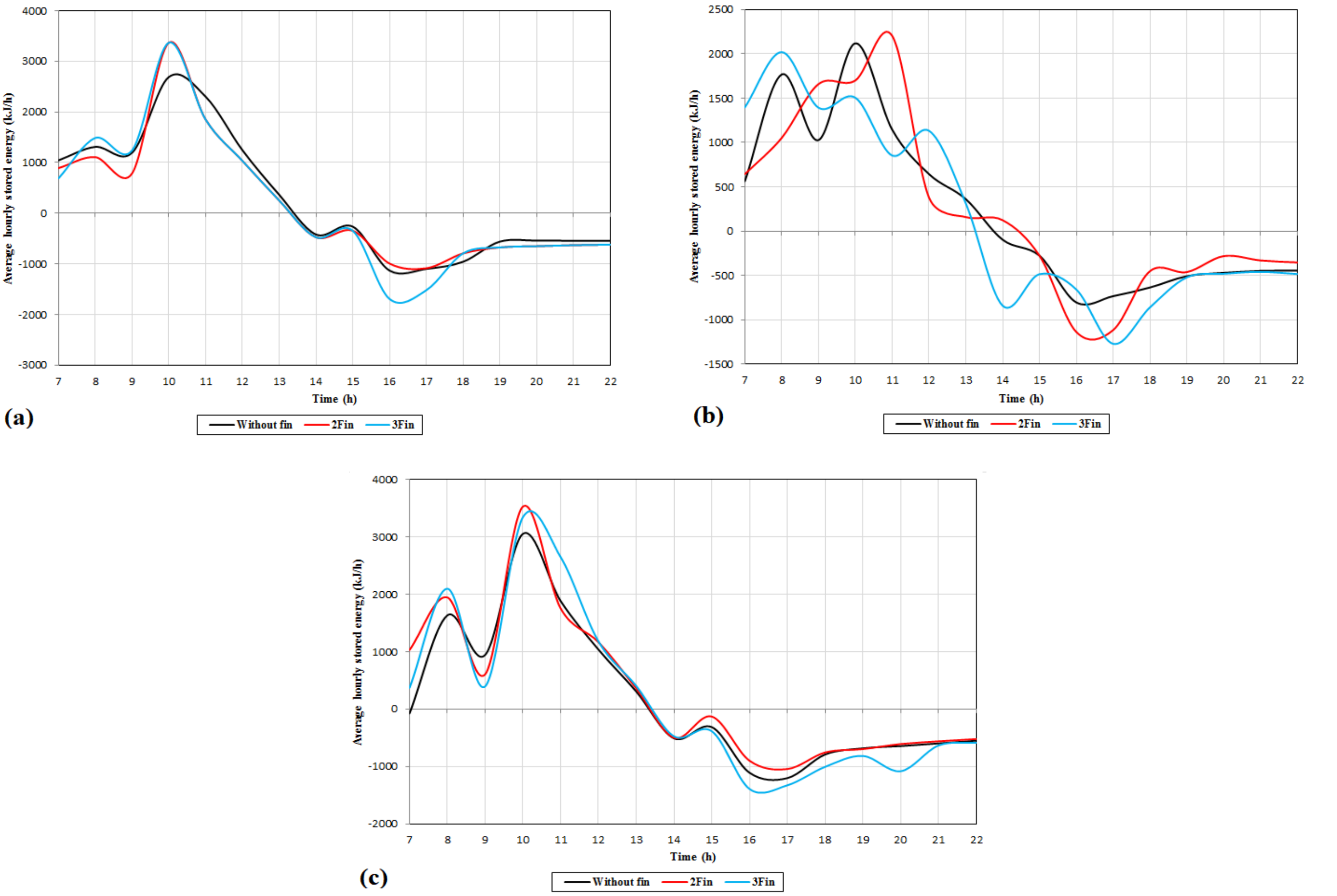


Fig. 17. Average variation of hourly stored energy within the Trombe wall for (a) brass, (b) aluminum, and (c) copper fins

Figs. 18 and 19 indicate the variation of Rayleigh number and convection heat transfer coefficient inside the channel and on the absorber respectively. Increase of fin number enhances convection heat transfer inside the channel and as a result, both Rayleigh number and the convection heat transfer coefficients increase. Furthermore, when the copper fins are used, the variation trend of both Rayleigh number and the convection heat transfer coefficients remained unchanged in the late hours of the day because the high stored energy in this case avoided a sharp decrease in the absorber temperature variation compared to two other fin types. Consequently, the temperature difference between the absorber and the channel glass was also influenced that almost kept the both aforementioned variation trends constant.

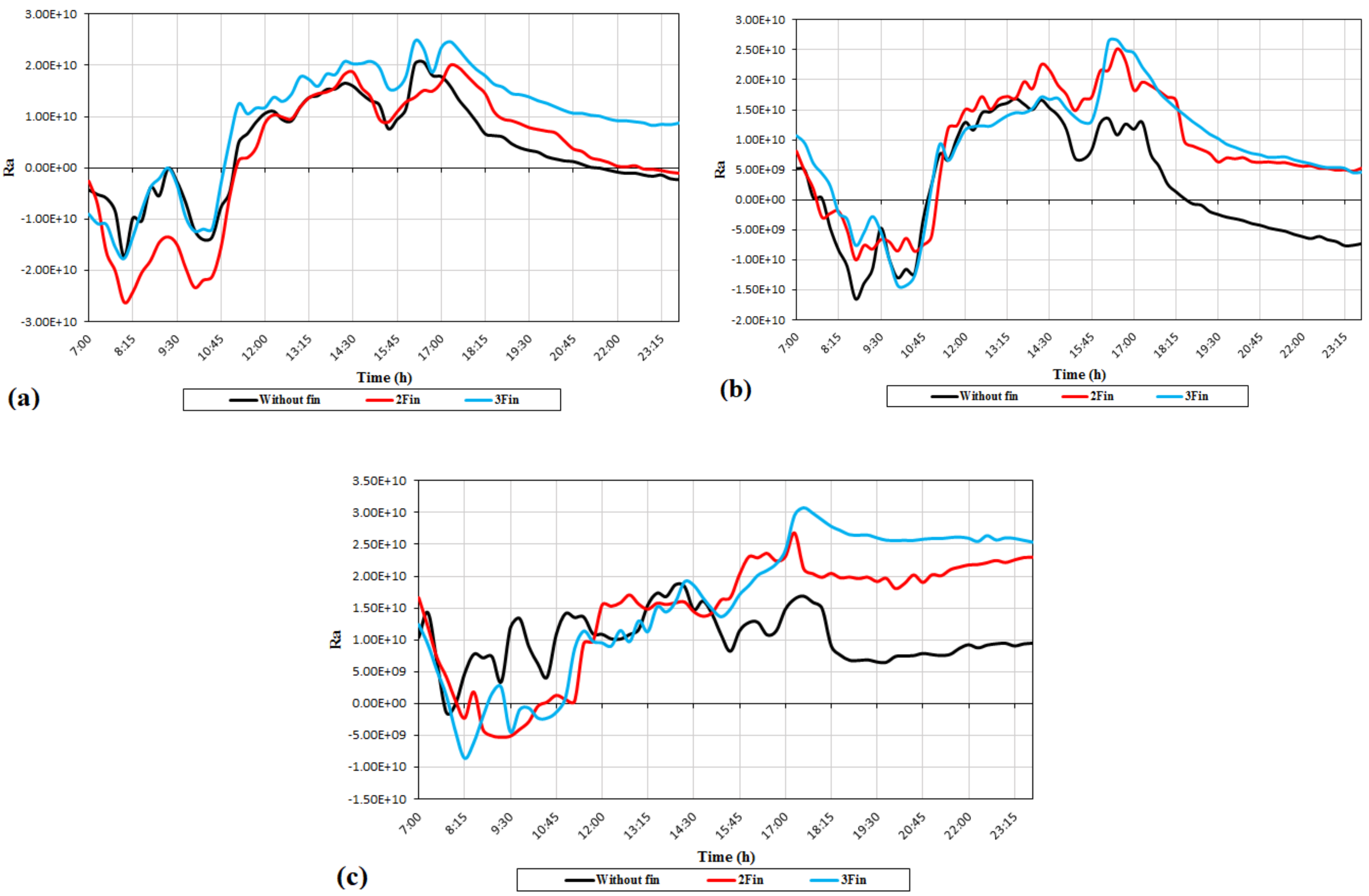


Fig. 18. Rayleigh number variation inside the channel for (a) brass, (b) aluminum, and (c) copper fins

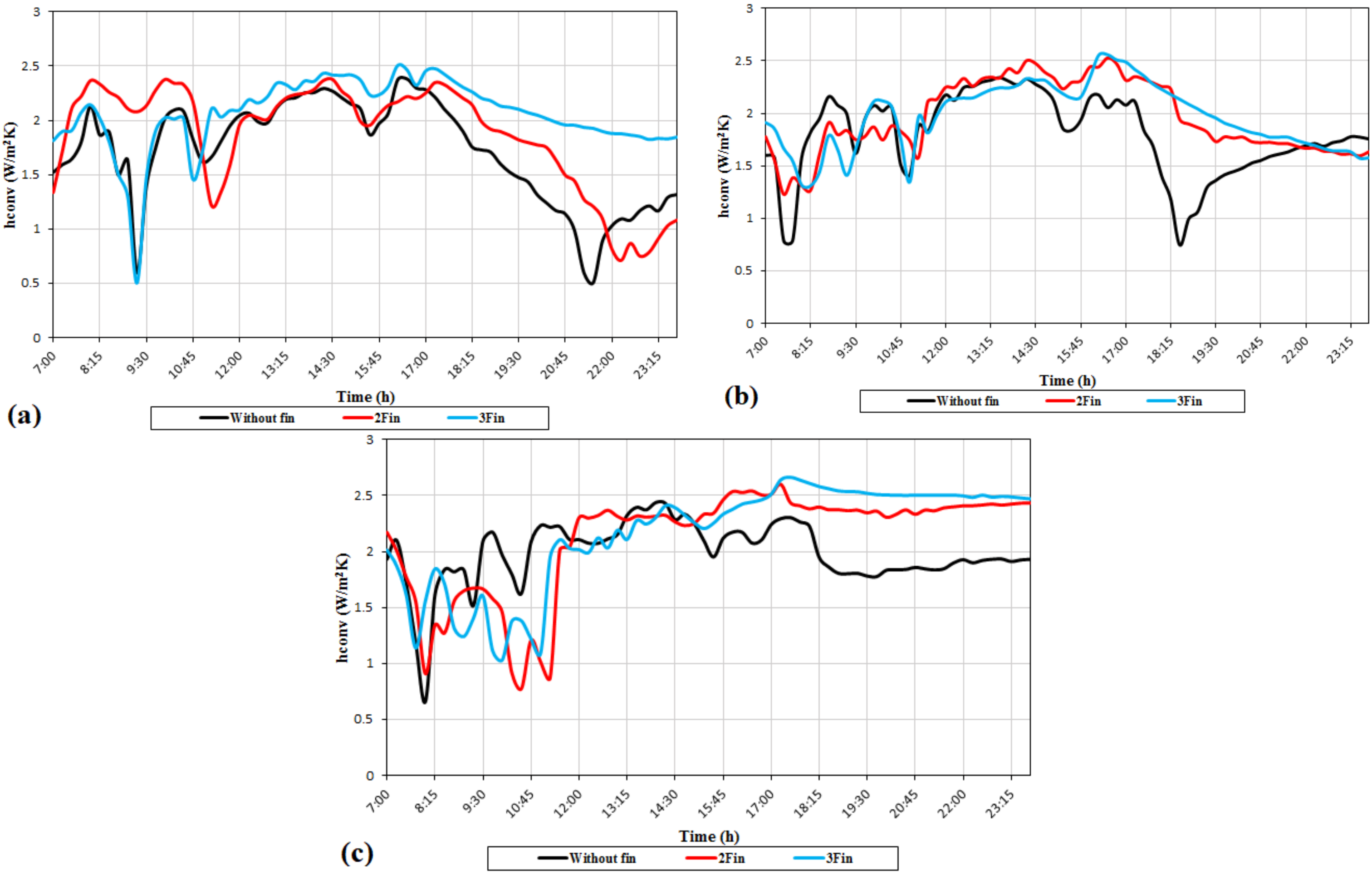


Fig. 19. Variation of convection heat transfer coefficient on the absorber for (a) brass, (b) aluminum, and (c) copper fins

Figs. 20 and 21 demonstrate the heating efficiency of the system with respect to the stored energy within the Trombe wall and the natural convection heat transfer respectively. With regard to the stored energy, the heating efficiency of the system with two copper fins and three brass fins was higher than other cases. However, based on the natural convection heat transfer, three copper fins resulted in higher heating efficiency in comparison with other cases.

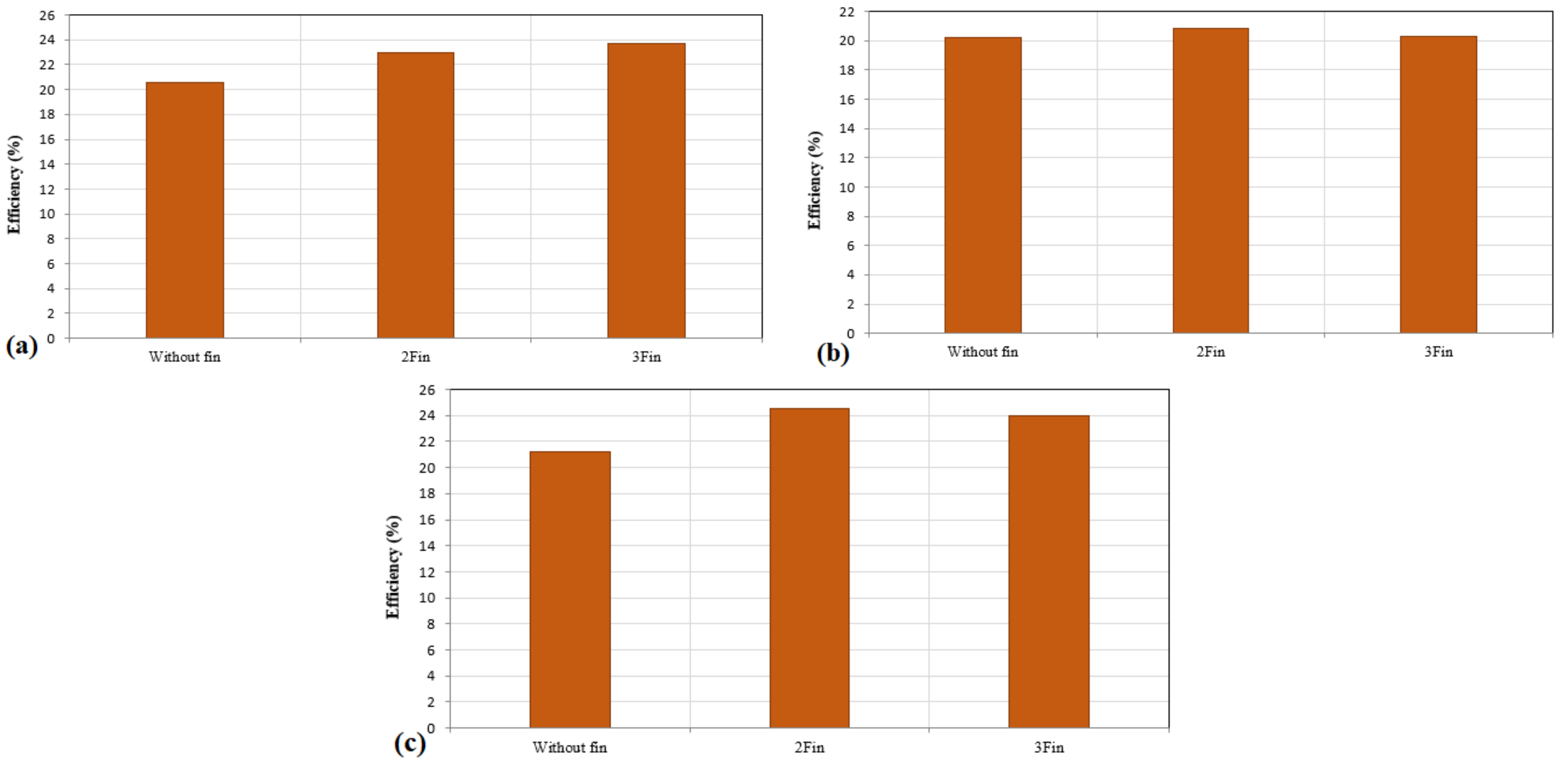


Fig. 20. System heating efficiency based on the stored energy within the Trombe wall for (a) brass, (b) aluminum, and (c) copper fins

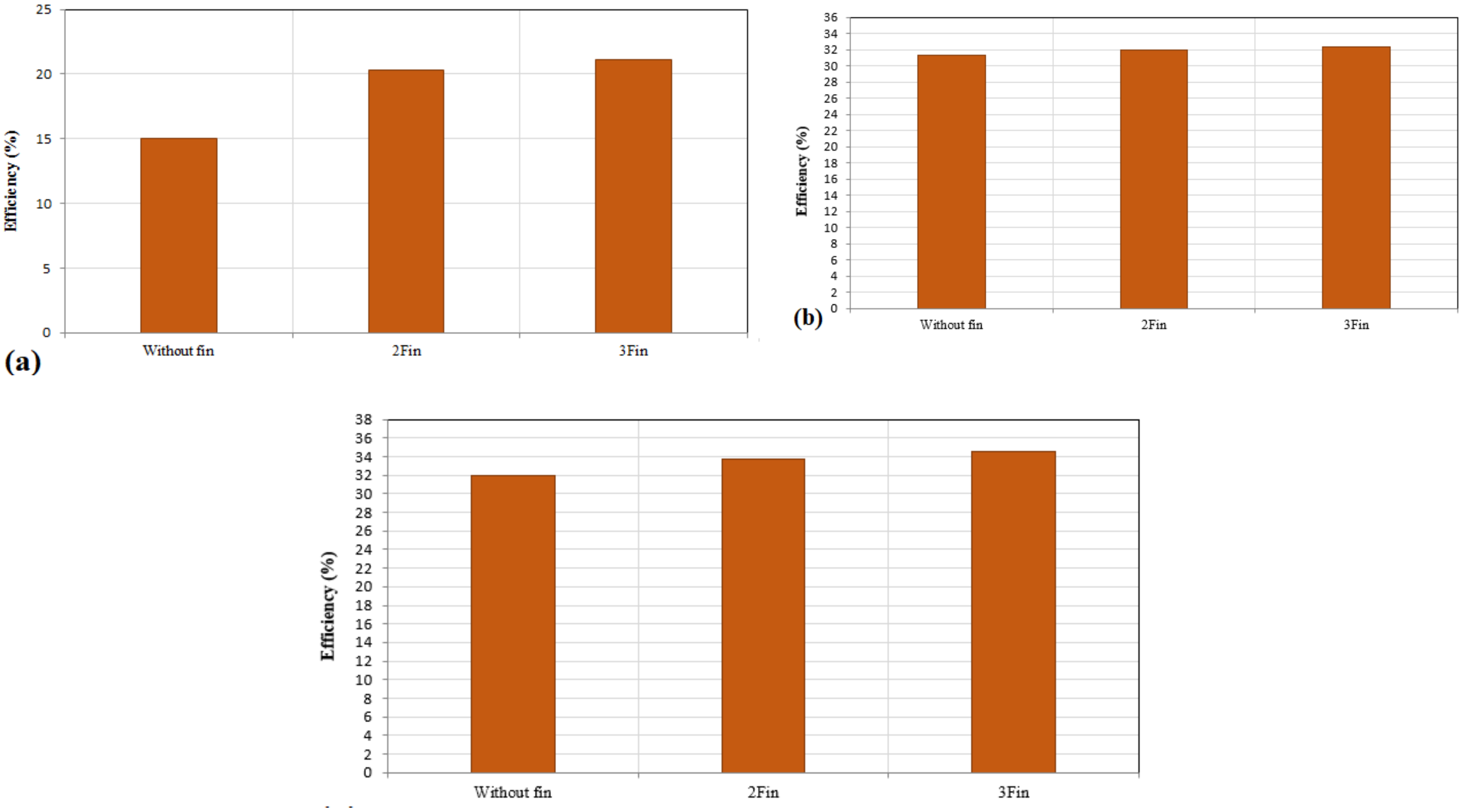


Fig. 21. System heating efficiency according to the natural convection heat transfer for (a) brass, (b) aluminum, and (c) copper fins

4. Conclusion

The present study investigated the heating performance enhancement of a new design Trombe wall using rectangular thermal fin arrays. The experimental results were found as follows:

1. Regarding the analysis of fin type effect on the heating performance of the Trombe wall system, the interior dimensions were 3m×2m×3m, the average temperature of the room was about 24-25°C, and the average temperature of the channel was around 25-28°C for all cases. Analysis of the fin type effect showed that the copper fin had the maximum heating efficiency of the Trombe wall system due to higher rate of natural convection heat transfer inside the channel. Comparing the aluminum and copper fins, both fin types produced almost similar temperature distribution inside the room space. However, regarding the heating efficiency of the system, the copper fin resulted in more desirable condition inside the room than aluminum fin.

2. Regarding heating performance of the Trombe wall system when fin number effect is the matter of concern, the interior dimensions were 3m×2m×3m, the average temperature of the room was measured about 27-30°C for copper, 17-20°C for brass, and 19-21°C for aluminum fin. Furthermore, the average temperature of the channel was about 28-33°C for copper, 24-26°C for brass, and 26-28°C for aluminum fin. The Effect of fin number revealed that the aluminum and copper fins with the same number of fins led to almost similar temperature distribution inside the room. With regard to the heating efficiency

of the system, no significant difference was observed for two and three copper fins. Nevertheless, better conditions than the copper fins were created.

3. It can be concluded that adopting thermal fin on the absorber could be considered as a practical way of enhancing the heating efficiency of the Trombe wall, about 5% and 7% based on the stored energy and rate of natural convection heat transfer criteria, respectively.

4. As a continuation of our work, the effect of number and type of fins on the cooling performance of Trombe wall with new channel design combined with water spraying system will be considered. It would be also interesting to see the effect of channel shape on the system performance. Furthermore, for the current system with thermal fins, it is suggested to consider the effect of different materials especially phase change material (PCM), integrated either to the room envelope or inside Trombe wall, on the performance of this new Trombe wall system in comparison with a typical Trombe wall system.

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