Performance Comparison of Dish Solar Collector System with Mirror Arrays & Receiver Shapes

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Abstract: The thermal performance comparisons of the dish solar collector system are numerically investigated with mirror arrays and receiver shapes. In order to compare the performances of the dish solar collector systems, six different mirror arrays and four different receiver shapes are considered and the radiative heat flux distribution on the inside of the receiver is analyzed. The solar irradiation reflected by mirrors is traced using the Monte-Carlo method. The results show that the dome type has the best performance in receiver shapes and the 2AND4INLINE has the best performance in mirror arrays except the perfect mirror.

Keywords: dish solar collector, mirror array, receiver shape, radiative property.

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1 Introduction

There are three categories in solar power generation, which are low temperature (below 100℃), mid temperature (100℃～300℃), high temperature (above 300℃). Also, solar concentrators used in the mid and high temperature are sorted by geometry, Vacuum tube collector, PTC (parabolic Trough concentrator), CPC (Compound Parabolic Concentrator), Dish solar collector system, and Solar tower (Ryu 2001).

A highly concentrating solar technology is fast growing and it is necessary to develop the technology of high efficiency optical system. In high temperature solar energy application, the dish solar collector system is one of the most remarkable systems. To successfully operate the dish solar collector system, the optimal design of the receiver is very important and flux density distribution has to be known (Kang 2004).

In high temperature solar energy application, the dish solar collector system is currently being developed for application in industrial process heat, electric generation and chemical reactor. In recent activity, ANU SG3 dish (400 kWth) was installed in Canberra, Australia by the Australian National University (ANU). Phase II (25 kWe) of the Boeing/Stirling Energy Systems Dish Engine Critical Components (DECC) project was installed in Huntington Beach, California, United States. Also, SAIC/STM (30kWe) was installed in Golden, Colorado and Phoenix, Arizona as a second USA project. In Europe, DISTAL (9kWe) I was installed by SBP and DLR at the Plataforma Solar de Almera (PSA) in Spain (Mills 2004).

In Korea, the researches for KIERDISH Ⅰ and KIERDISH Ⅱ have been carried out by Korea institute of energy research (KIER). These have been installed, operated until now. Therefore, the sufficient technology for the dish solar collector system might be prepared. However, in order to develop the more efficient and cheaper system, the researches for the design factor such as the mirror arrays and the receiver shapes must be investigated.

Therefore, in this study, the performance comparisons are numerically investigated with the mirror arrays and the receiver shapes of the dish solar collector system. For this, six different mirror arrays and four different receivers are proposed in this study. Six different mirror arrays are perfect mirror, 2AND4INLINE, 2TOP, INLINE, STAGGERED and STAR. Four different receiver shapes are a dome, a conical, a cylindrical and a unicorn type. In order to analyze the performance comparison of the dish solar collector system, the radiative heat flux distribution on the inside of the receiver is numerically investigated. In addition, the radiative properties of the mirror surface can vary the thermal performance of the dish solar collector system so that the effects of the surface reflectivity and the surface absorptivity are considered.

2 Modeling

To compare the performances of the dish solar collector systems with mirror arrays, the perfect mirror is determined as the reference of the mirror array. Fig. 1 shows the dish solar collector consisted of the perfect mirror. The perfect mirror is 1.4 m in diameter and has a f/D of 0.93. The mirror surface is a parabolic shape. The receiver is positioned at the focal region of the perfect mirror.

As shown in Fig. 2, five different mirror arrays which have the reflecting area equal to the perfect mirror are proposed. The each mirror array consists of twelve mirror facets of which diameter and focal length are 0.41 m and 1.5 m. The surface of each mirror is the parabolic shape and the receiver is positioned at the focal region of the mirror.

In order to compare the performance of the dish solar collector system with receiver shapes, four different receiver shapes are suggested as shown in Fig. 3. The width and height of each receiver are assumed to be 160 and 170. Also, the aperture diameter of each receiver is assumed to be identically 150 mm.

To analyze the radiative heat flux distribution on the inside of the receiver, the TracePro, which is based on the Monte Carlo method, is used in this study. This method involved the use of a random number generator to model the statistical processes of photon emission, non-specular reflection, and absorption. Photons are distributed uniformly at the aperture of mirror. The paths of individual photon bundle are traced through the optical system using geometry, and a tally made of the ultimate fate of the bundles. Ray tracing is repeated until photon bundle is absorbed in the receiver surface or come out the receiver cavity. After half a million photon bundles are through the system, the radiative heat flux distribution at the receiver is determined. The number of entered photon bundles in the receiver is N, and then the number of absorbed photon bundles in the receiver surface is Na. Radiative heat loss due to surface reflection is calculated using the following equation (Ryu 2000).

$$Q_{RL} = Q_{in} \frac{N - N_a}{N} \qquad (1)$$

By using the above processes, in order to analyze the radiative heat flux distribution at the focal region of the solar dish concentrator, a circular plane characterized by blackbody on the surface is positioned at the focal region of the solar dish concentrator. And, photon bundles are emitted parallel and have the annual-average daily direct normal solar radiation 4.4～4.8 kWh/ (Jo 1991). Also, all photon bundles are incident perpendicular to the aperture of mirror.

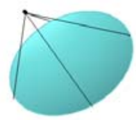


Figure 1 Array of mirror (Case Ⅰ: Perfect mirror) (Thomas 1991)

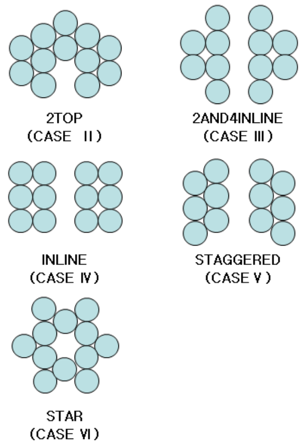
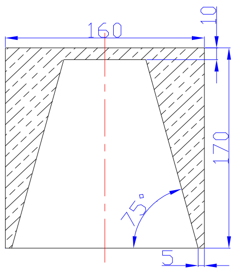
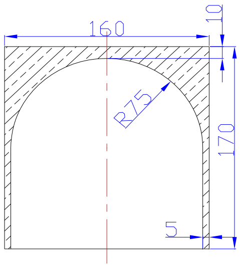


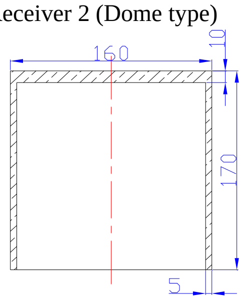
Figure 2 Array of mirrors (Case Ⅱ-Ⅵ) (Thomas 1991)



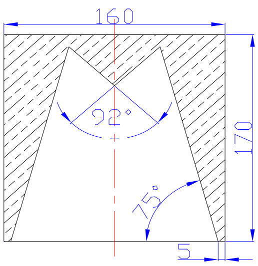
Receiver 1 (Conical type)



Receiver 2 (Dome type)



Receiver 3 (Cylindrical type)



Receiver 4 (Unicorn type)

Figure 3 Receiver shapes (Ryu 2001)

3 Results and Discussion

3.1 Radiative heat flux distribution at the focal plane

The radiative heat flux distribution at the focal plane with mirror arrays is shown in Fig. 4. The optical properties of the mirror surface are the total hemispherical reflectivity 0.9 and the total hemispherical absorptivity 0.1, respectively. As shown in Fig. 4, the radiative heat flux distribution of the dish solar collector system at the focal plane is different with the mirror arrays. The radiative heat flux distribution of Case Ⅰ is the densest in all cases. On the other hand, those of Case Ⅲ, Ⅳ, Ⅴ and Ⅵ are relatively broad. That of Case Ⅱ is the densest in the multi-faceted mirror arrays.

In actual dish solar collector system, the aperture diameter of the receiver should be determined differently with mirror arrays. However, in this study, that is determined identically for the performance comparison. The aperture diameter of the receiver should be able to intercept approximately 90% of the incident radiation. Based on Fig. 4, the minimum diameter of the receiver is found to be 0.15 m.

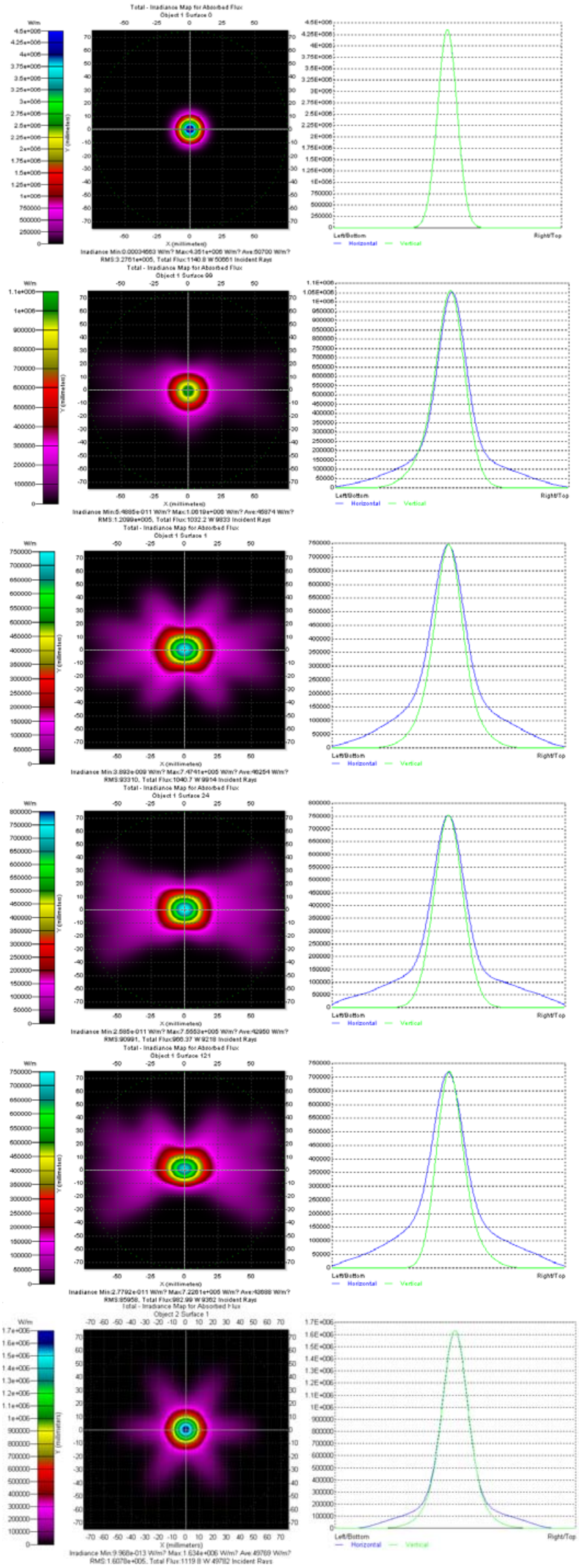


Figure 4 Radiative heat flux distribution at the focal plane (Case Ⅰ-Ⅵ)

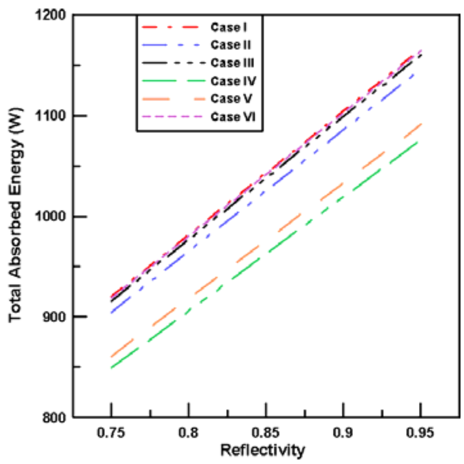
3.2 Total absorbed energy with the reflectivity of the mirror surface

Fig. 5 shows the total absorbed energy on the receiver inner surface with the reflectivity of the mirror surface. As shown in Fig. 5, as the reflectivity increases, the total absorbed energy increases linearly for all the cases and the slopes of all the cases are identical. These results show that the performance of the dish solar collector system is varied linearly with the reflectivity of mirror surface and the mirror surface reflectivity is a major factor for the performance improvement.

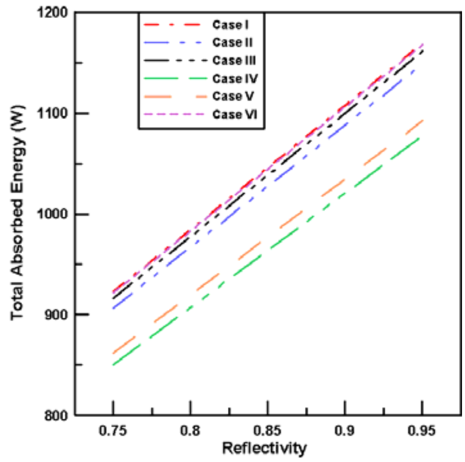
As expected, the total absorbed energy of Case Ⅰ is higher than those of others in Fig. 5. And, the total absorbed energy of Case Ⅳ is smallest among six other cases. Case Ⅵ has the best performance in the multi-faceted mirror arrays.

The performances of dish solar collector system with mirror array and reflectivity variation are summarized in Table 1-4. As shown in Table 1-4, Case Ⅰ has the best performance and Case Ⅳ has the worst performance in all cases. Case Ⅵ shows the best performance except Case Ⅰ. By comparing calculated results, the difference between Case Ⅰ and Case Ⅲ is less than 1 %. On the other hand, the difference between Case Ⅰ and Case Ⅳ is about 8 %. This result shows that performance improvement of dish solar collector system will be possible about 7 % by optimizing the mirror arrays considered in this study.

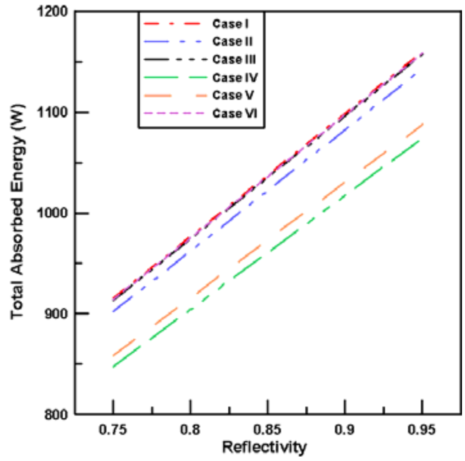
Based on Fig. 5 and Table 1-4, the combination with receiver 4 and Case Ⅰ has the maximum total absorbed energy at reflectivity 0.95 and the combination with receiver 4 and Case Ⅳ has the minimum total absorbed energy at reflectivity 0.75. The difference between maximum value and minimum value is 29 %. Also, these results show that when the receiver 4 is used, the performance of the dish solar collector is the highest in all cases.



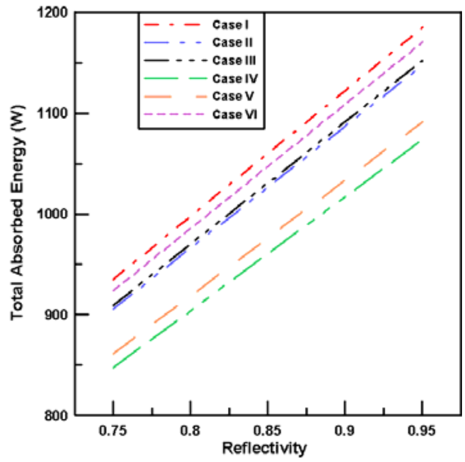
(a) Receiver 1



(b) Receiver 2



(c) Receiver 3



(d) Receiver 4

Figure 5 Total absorbed energy with reflectivity of mirror surface (Receiver 1-4)

Table 1 Total absorbed energy in receiver 1 with reflectivity and mirror array [Unit : W]

	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅳ
0.75	920.10	904.66	915.75	849.29	860.95	918.75
0.8	981.49	964.97	976.80	905.91	918.34	980.00
0.85	1042.89	1025.29	1037.85	962.53	975.74	1041.26
0.9	1104.30	1085.60	1098.90	1019.15	1033.14	1102.51
0.95	1165.71	1145.91	1159.95	1075.76	1090.54	1163.76

Table 2 Total absorbed energy in receiver 2 with reflectivity and mirror array [Unit : W]

	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅳ
0.75	922.98	906.55	916.37	850.35	862.13	921.57
0.8	984.51	966.99	977.46	907.04	919.60	983.018
0.85	1046.05	1027.43	1038.55	963.73	977.08	1044.46
0.9	1107.59	1087.86	1099.64	1020.42	1034.55	1105.89
0.95	1169.13	1148.30	1160.74	1077.11	1092.03	1167.33

Table 3 Total absorbed energy in receiver 3 with reflectivity and mirror array [Unit : W]

	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅳ
0.75	915.44	902.03	913.38	847.71	858.58	914.25
0.8	976.52	962.17	974.28	904.23	915.82	975.20
0.85	1037.61	1022.30	1035.17	960.74	973.06	1036.15
0.9	1098.71	1082.44	1096.06	1017.26	1030.30	1097.10
0.95	1159.81	1142.57	1156.95	1073.77	1087.54	1158.06

Table 3 Total absorbed energy in receiver 4 with reflectivity and mirror array [Unit : W]

	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅳ
0.75	935.25	905.67	909.32	847.39	861.22	923.83
0.8	997.60	966.04	969.94	903.89	918.63	985.42
0.85	1059.95	1026.42	1030.56	960.38	976.05	1047.01
0.9	1122.30	1086.80	1091.19	1016.87	1033.46	1108.60
0.95	1184.65	1147.18	1151.81	1073.37	1090.88	1170.19

3.3 Total absorbed energy with the absorptivity of the receiver surface

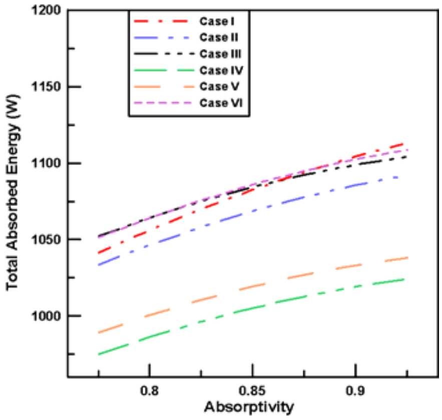
Fig. 6 shows the total absorbed energy of the receiver inner surface with the absorptivity of the receiver inner surface. As shown in Fig. 6, as the absorptivity increase, the total absorbed energy increases gradually but the growth rate decreases. The slope of Case Ⅰ is steeper than those of the others.

In case of receiver 1, the performance of Case Ⅲ is the best when the absorptivity is less than 0.8. On the other hand, that of Case Ⅵ becomes the best performance when the absorptivity is from 0.825 to 0.875. That of Case Ⅰ becomes the best when the absorptivity is more than 0.9. Case Ⅳ has the worst for all absorptivities. In case of receiver 2, the performance of Case Ⅵ is the best when the absorptivity is less than 0.875. On the other hand, that of Case Ⅰ becomes the best performance when the absorptivity is more than 0.9. Case Ⅳ has the worst for all absorptivities. In case of receiver 3, the performance of Case Ⅲ is the best when the absorptivity is less than 0.875. On the other hand, that of Case Ⅰ becomes the best performance when the absorptivity is more than 0.9. Case Ⅳ has the worst for all absorptivities. In case of receiver 4, the performance of Case Ⅰ has the best for all absorptivities. Case Ⅳ has the worst for all absorptivities.

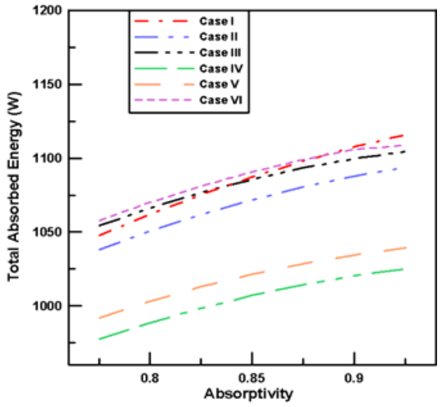
Table 5-8 show the performance of the dish solar collector system with the mirror arrays and the absorptivity. In the previous chapter, Case Ⅰ has the best performance for all cases. However, the results of this chapter show that the Case Ⅲ, Ⅵ have the best performance for low absorptivity but Case Ⅰ has the best performance for high absorptivity. This is because as the absorptivity of the receiver surface increases, the effects of the re-reflection in the receiver decrease. Therefore, Case Ⅰ which has the small focal region has the best performance for high absorptivity. On the other hand, Case Ⅲ, Ⅵ which have the broad focal region show the best performance for low absorptivity. However, the difference between Case Ⅰ and Case Ⅲ, Ⅵ is less than 3%.

The difference between Case Ⅰ and Case Ⅳ is 6.4% for absorptivity 0.775 and 8.2% for absorptivity 0.925. This result shows that the performance difference increases as the absorptivity increases.

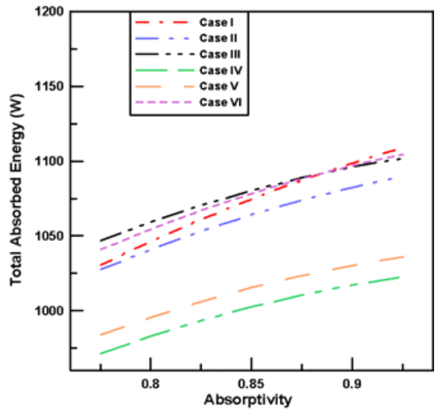
Based on the Fig. 6 and Table 5-8, the combination with Case Ⅰ and the receiver 4 has the maximum value at absorptivity 0.925, and the combination with Case Ⅳ and the receiver 4 has the minimum value at absorptivity 0.775. Therefore, the performance improvement of the dish solar collector system will be possible about 29% according to the receiver shape and the absorptivity of the receiver surface.



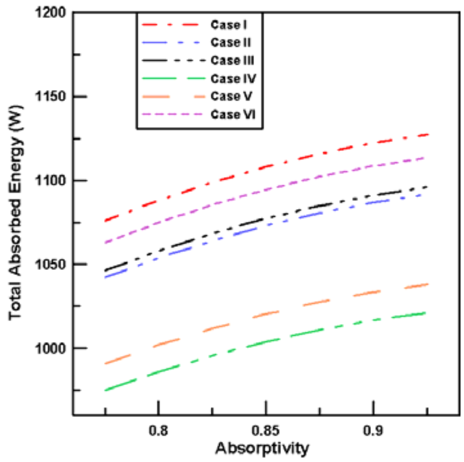
(a) Receiver 1



(b) Receiver 2



(c) Receiver 3



(d) Receiver 4

Figure 6 Total absorbed energy with absorptivity of receiver surface (Receiver 1-4)

Table 5 Total absorbed energy in receiver 1 with absorptivity and mirror array [Unit : W]

	I	II	III	IV	V	IV
0.775	1041.37	1033.73	1052.34	975.04	989.27	1051.30
0.8	1056.29	1046.66	1064.39	986.38	1000.62	1064.20
0.825	1070.05	1058.31	1075.07	996.46	1010.68	1075.73
0.85	1082.63	1068.68	1084.38	1007.09	1019.45	1086.00
0.875	1094.05	1077.78	1092.33	1012.84	1026.94	1094.90
0.9	1104.30	1085.60	1098.90	1019.15	1033.14	1102.50
0.925	1113.39	1092.15	1104.11	1024.20	1038.06	1108.80

Table 6 Total absorbed energy in receiver 2 with absorptivity and mirror array [Unit : W]

	I	II	III	IV	V	IV
0.775	1047.75	1038.12	1054.43	977.51	992.01	1057.86
0.8	1062.15	1050.69	1066.25	988.64	1003.13	1070.19
0.825	1075.33	1061.95	1076.68	998.50	1012.95	1081.16
0.85	1087.30	1071.89	1085.73	1007.09	1021.45	1090.77
0.875	1098.05	1080.54	1093.38	1014.39	1028.66	1099.01
0.9	1107.59	1087.87	1099.65	1020.43	1034.56	1105.89
0.925	1115.92	1093.89	1104.53	1025.18	1039.15	1108.80

Table 7 Total absorbed energy in receiver 3 with absorptivity and mirror array [Unit : W]

	I	II	III	IV	V	IV
0.775	1030.54	1027.61	1046.84	971.38	983.77	1040.84
0.8	1046.35	1041.04	1059.34	983.02	995.573	1054.57
0.825	1061.08	1053.24	1070.52	993.43	1006.13	1067.07
0.85	1074.71	1064.21	1080.36	1002.6	1015.43	1078.32
0.875	1087.26	1073.94	1088.88	1010.5	1023.49	1088.33
0.9	1098.71	1082.44	1096.07	1017.3	1030.31	1097.11
0.925	1109.08	1089.71	1101.92	1022.7	1035.87	1104.64

Table 8 Total absorbed energy in receiver 4 with absorptivity and mirror array [Unit : W]

	I	II	III	IV	V	IV
0.775	1076.24	1042.20	1046.41	975.150	991.06	1063.11
0.8	1088.29	1053.87	1058.12	986.064	1002.15	1075.01
0.825	1098.92	1064.16	1068.45	995.693	1011.93	1085.51
0.85	1108.13	1073.08	1077.41	1004.03	1020.42	1094.60
0.875	1115.92	1080.62	1084.99	1011.10	1027.59	1102.30
0.9	1122.30	1086.80	1091.19	1016.87	1033.46	1108.60
0.925	1127.26	1091.60	1096.01	1021.37	1038.03	1113.50

3 Conclusions

The thermal performance of the dish solar collector system is numerically investigated according to the mirror arrays and the receiver shapes.

1. The total absorbed energy in the receiver increases linearly as the reflectivity of the mirror surface increases.
2. The total absorbed energy in the receiver increases gradually as the absorptivity of the receiver surface increases.
3. Based on the calculated results, Case VI (STAR) has the best performance and Case IV (INLINE) has the worst performance in the multi-faceted mirror arrays.
4. Based on the calculated results, the Unicorn type has the best performance in the four receivers.

Consequently, the results show that the combination with Case VI (STAR) and the receiver 4(Unicorn type) is optimal in all the combinations considered in this study.

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