A Study of a Non-imaging Concentrator and Its Application on Solar Energy

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論 文 内 容 要 旨

Chapter 1: General introduction and background

Chapter 1 describes a background of this study. The importance of the energy for humanity and recent problems related with energy were discussed. To solve these problems, the requirement of alternative energy sources was indicated. Among the renewable energy source, the significance of the solar energy was considered. To utilize the solar energy by converting to heat or electricity, conventional methods including photovoltaic and solar collectors were discussed. Finally, the non-imaging optics in solar collector was explained. The current problems to solve such as performance reduction with aging and because of heat loss, non-uniform illumination around absorber, difficulties in maintenance of the concentrator systems and also additional cost due to sun tracking system in the conventional collectors were found.

Chapter 2: Non-imaging optics and theoretical modelling for performance

In this chapter, the theory of the non-imaging optics and conventional non-imaging concentrators were discussed. Their advantages to imaging concentrators and to each other were discussed. In order for the performance evaluation method of the proposed concentrator and for analyzing the thermal behavior of the absorber under the solar insolation, a calculation method was written by using ray tracing analysis. The principle of the ray-tracing procedure was explained in detail. The optical efficiency which is a function of absorptivity, transmissivity and reflectivity, was explained and its evaluation method was expressed. The thermal analysis methods of the absorber to determine the uniformity was explained by considering of analytical and numerical evaluations. Finally, a thermal efficiency evaluation method was explained. Additionally, the optical properties on the surface of the absorber were discussed. The spectral selective coating was discussed which improves the absorptivity of absorber for solar radiation in visible region with decreasing the thermal emissivity in far infrared region. Introduced methods in this chapter were used in following chapters.

Chapter 3: Proposal of a non-imaging concentrator and its performance evaluation

In this chapter, a two-stage line axis and non-imaging concentrator was proposed and investigated. The design of the concentrator was based mainly on the goals of exploiting the low-heat loss configuration, uniform temperature distribution on the absorber and approaching the highest possible concentration by the reflectors. The ray-tracing method was used to evaluate its optical and thermal efficiency as a function of the incidence angle of solar irradiance and the absorber temperature for a 2-D model. The geometry of the proposed design was expressed in detail. The maximum acceptance angle was calculated for Sendai, Japan to be 23.44°.

The optical performance as function of the incident angle was evaluated and the best performance is observed for an incident angle of 12.7° to be 76.8°. Furthermore, the solar heat flux distribution and temperature distribution around the absorber were analytically and numerically analyzed to evaluate temperature uniformity for different absorber materials. The results showed that the copper and aluminum absorber materials have quite uniform distribution. For the case of stainless steel, the difference between maximum and minimum temperature of points on the absorber was small enough to assume as uniform with only about 2 °C differences. The proposed solar concentrator was compared to different conventional stationary collectors as seen in Fig. 1.. At the boiling point of water, 373 K, the concentrator operates with a reasonably high average thermal efficiency of 47.8 %, although the absorber was assumed to have a gray surface.

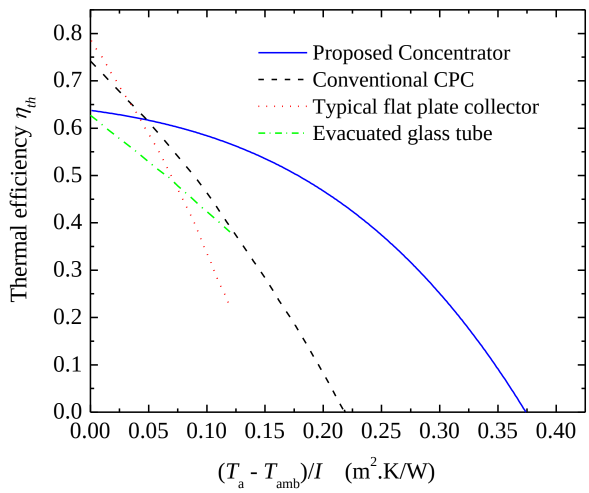

Fig.1 Comparison of thermal efficiency in terms of absorber temperature

Chapter 4: Development and modifications of the proposed concentrator

In this chapter, the proposed solar concentrator was modified to improve the performance with reducing the manufacturing cost. The developed models were evaluated in terms of optical and thermal performance.

First, the proposed concentrator was considered in terms of truncation. Due the steep angle at the end of compound parabolic reflector, the concentrator allows to truncation with a slight reduction in the concentration ratio. To decide the optimum level of truncation, several method were carried out including evaluation of ray acceptance, and optical and thermal efficiency of the reflector and temperature uniformity around the absorber for different truncation level. The optical and thermal efficiency of the concentrator as a function of reflector length is shown in Fig. 2.

In order to obtain more uniform illumination; different truncation levels of the proposed concentrator were considered. Uneven distribution effect and intense radiation regions are significantly minimized for the optimum truncation level of 50 %. The average optical performance increased slightly while the truncation level increased. The attenuation on the performance for the incident angle that closes the acceptance angle is minimized due to less number of reflections. Moreover, the some rays out of the maximum acceptance angle can reach the absorber directly or via involute reflector while no ray can reach the absorber out of the maximum acceptance angle in the case of full concentrator. The thermal efficiencies of the truncated concentrators were slightly better than full concentrator for the selective coating absorber case since the selective coating reduces the radiative heat loss effect on the performance.

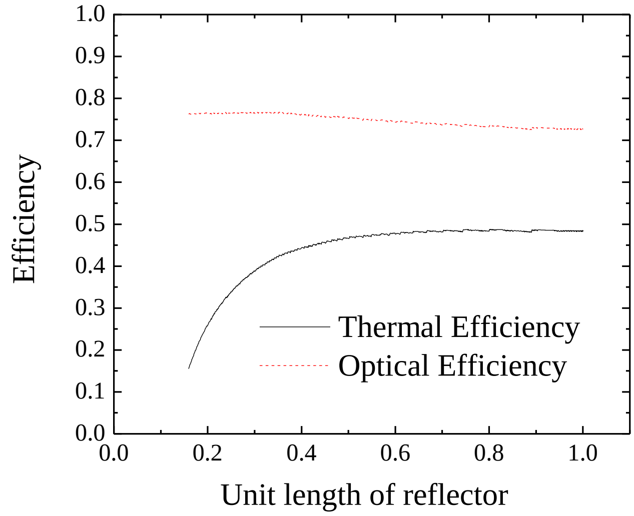

Fig. 2 Thermal and optical efficiency of the concentrator as a function of reflector length

Additionally, in order to obtain better ray acceptance which is the ratio of the reflector aperture area to the glass cover diameter, a dual form of the concentrator, which consists of two identical proposed concentrators in one glass tube, was evaluated. The ray acceptance of dual concentrator was about 20 % better than that of single concentrator. Besides improved ray acceptance, this configuration is advantageous for multiple concentrator unit applications due to its comparatively less glazing material requirement. The circumference of the glass tube for dual concentrator was increased only by 28 %. Namely, less glass material will be required to cover two proposed concentrator Furthermore, the proposed design facilitates the applicability of U-type absorber tube and eliminates the requirement for the unilateral insolation cap on the vacuum glass tube.

Chapter 5: Annual and seasonal performances of the proposed concentrator

In this chapter, the proposed concentrator is evaluated in daily and annual performance. During a day or during seasonal variation some rays reach the concentrator's reflectors at oblique angles. Therefore, a calculation method was adapted to analyze seasonal performance by using 2D ray tracing analysis.

The relationship between the sun and earth is described in detail in terms of incident angle and other solar trajectory parameters. The performance evaluations were conducted on heat generation and thermal efficiency for daily and annual respond and for different designs of the proposed system. The proposed concentrator showed a preferable performance for year around particularly for the equinox and nearby times with a solar utilization for almost whole day time. However, the efficiency decreased significantly for the days which are close to winter and summer solstice and solar utilization times reduced to about 2 hours. In these days, most of the rays were coming out of the maximum acceptance angle in the early morning and late afternoon hours. To improve performance during this period, the truncated concentrators and concentrators with higher ray acceptance angle were considered. The truncated concentrator showed an improved performance for the days which is close the solstice days. Another alternative was to increase the acceptance angle. Therefore, several concentrators which have different concentration ratio were considered for gray and selective surface absorber cases. At least for 8 hours solar utilization in the solstice days, a concentrator which has a selective surface absorber and an acceptance angle of 40° was considered.

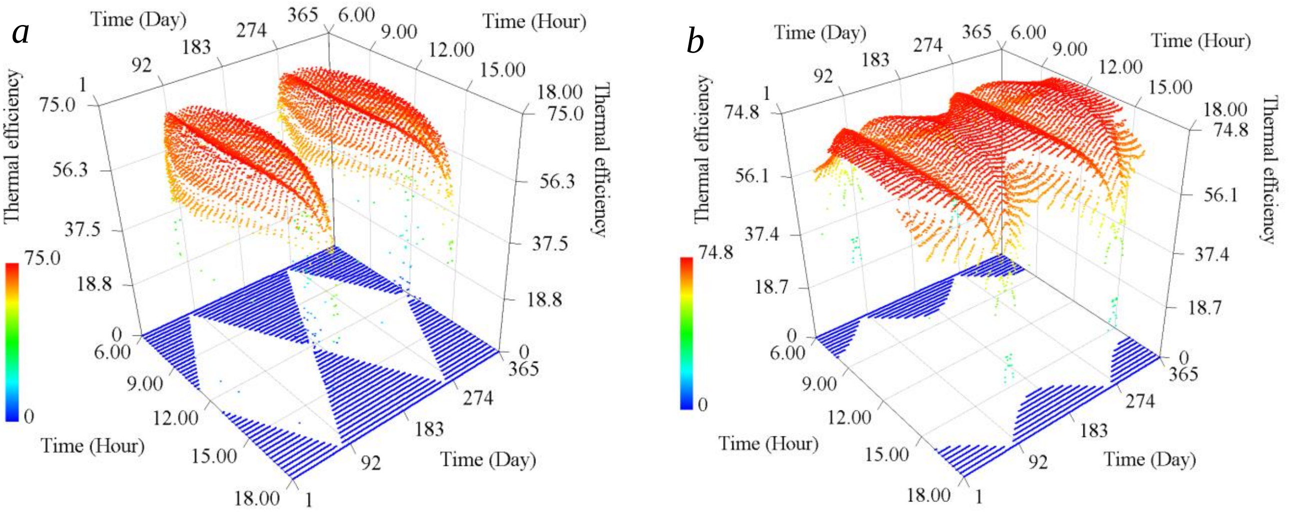

Fig.3 Annual performance of full concentrators with an acceptance angle of 23.44° (a) and 40° (b)

Chapter 6: Experimental evaluation of the concentrator in single and dual form

In this chapter, the proposed concentrator was evaluated experimentally to validate the theoretical calculation. The experiments were conducted to analyze the effect of proposed concentrators in energy collection in actual ambient conditions. The thermal performance of the proposed concentrator was evaluated. The experiment was done for vacuum and non-vacuum case of the single model concentrator in the partly sunny days. The theoretical model was simulated for the actual experimental conditions. In order to evaluate the models, the ambient temperature, absorber temperature, and water inlet and outlet temperature to and from the concentrator were measured and their interrelationship to each other was

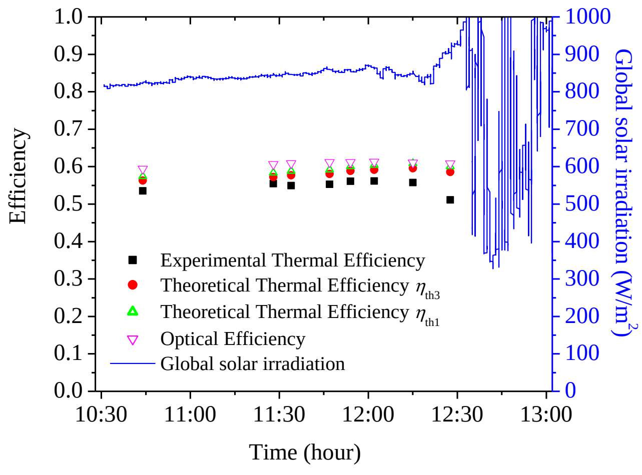

Fig.4 Experimental evaluation of the thermal efficiency

evaluated. The theoretical evaluation was conducted by determining the optical efficiency and heat loss from the absorber. The experimental results were determined by evaluating the input and output energy of the system. The input energy was considered as solar insolation on the aperture area of the concentrator and output energy was the energy variation between the outlet hot water and inlet cold water. Finally, the results of two models were compared to each other and obtained good agreement as seen in Fig. 4

Chapter 7: Evaluation of a solar power plant application

In this chapter, the proposed concentrator was considered in a power plant system due to its high efficiency for even high operation temperature. The Rankine Cycle and Organic Rankine Cycle were introduced. The Organic Rankine Cycle was considered more appropriate one because it is applicable for even small-scale power generation for use in residential and commercial buildings. Then several working fluids were tested to determine most appropriate one.

Energy analysis was conducted to determine which working fluids require less energy for the specified conditions. Among the selected working fluids, water, methanol and n-Hex-CC fluids need the highest energy to obtain the 100 % vapor fraction for the selected conditions, respectively. On the other hand, Refig-113, R-141b and Benzene require lowest energy. However, out power is also important to decide the efficiency.

The efficiency of the collector, cycle and overall system were evaluated. In order to decide the performance of the collector, as a first approximation, the output steam temperature from the absorber was assumed to be equal to average surface temperature of absorber. Thus the efficiency of the proposed system was decided for required conditions. The overall system efficiency was obtained by multiplying the efficiency of the collector and cycle system. The overall of system efficiency achieves the best performance for R-141and Refig-13. The efficiency of water, benzene, methanol, and cyclohexane are quite closes to each other. On the other hand, n-Decane, n-Hex-CC5, n- Nonane, n-Octane show significantly low thermal performance.

The differential pressure from the pump and turbine were changed as a calculation parameter. Thus, the efficiency improvement was evaluated and optimal level of compression was evaluated. The best improvement was observed for the change of differential pressure from 3bars to 9 bars. After the pressure change of 24 bars, the efficiency of the R-141b and Cyclohexane becomes stable. Namely, any increase in the differential pressure will not improve the overall system performance.

Chapter 8: General conclusions

The founding in this thesis is concluded. In this study, following result and knowledge were obtained.

1. The proposed design can eliminate the requirement of sun tracking due to non-imaging design and can eliminate the problems in conventional collectors.
2. Truncated concentrator is preferable due to its low material requirement with only slightly reduction in concentration ratio. The effect of this slight reduction can be eliminated by using selective coating.
3. The efficiency of seasonal performance can be improved by using a concentrator having higher ray acceptance or using a truncated design.
4. The theoretical evaluation was validated by making an experimental model. The results have good agreement.
5. In order to improve the effective life cycle and eliminate the requirement of sun tracking system, the proposed concentrator was considered as a steam generator in a solar power plant due to its high efficiency even for high temperature.

論文審査結果の要旨

太陽エネルギーは高密度な再生可能エネルギーとして有望視されている。太陽光を熱源として活用する機器として太陽集熱器がある。既存のものは，太陽光を結像し高熱流束を作り出すための複雑な追尾装置や，逆に集光せずに大面積で集熱する平板型集熱器などがあるが，複雑な構造，低い集光度，汚れに対して弱いなどの欠点がある。そこで本研究では非結像集光器に注目し，可動部がなく高い集光度を持ち，低熱損失な太陽集熱器を新たに提案し，その実用性について検討している。本論文は，これらの研究成果をまとめたものであり，全編８章からなる。

第１章は序論であり，本研究の背景，目的および構成を述べている。

第２章では，非結像集光器の光学理論およびその解析手法について述べている。太陽集熱器を評価するために本研究では，光学効率を算出するための光線追跡法，熱効率を評価するための伝熱形態について議論している。これは非結像集光器を解析するために重要な知見である。

第３章では，新たな非結像集光系を用いた太陽集熱器について述べている。提案した太陽集熱器は，複合放物面鏡とインボリュート型反射鏡を組み合わせた反射鏡を，真空管の中へ封じることにより，追尾機能無しでも年間を通して高い集光度を持ち，真空管に封じたため熱損失が低くなり，反射鏡が汚れないという特徴を有する。宮城県仙台市の位置で最適化した太陽集熱器は，平均光学効率 72.7%，採熱管温度 100℃における平均熱効率が 47.8%という性能を有することを明らかにしている。高性能な新型の太陽集熱器を提案しており，実用化も期待される重要な成果である。

第４章では，第３章で提案した太陽集熱器の別の形態での利用を検討している。一般的に長くなる複合放物面鏡の長さを半分にすることで，光学効率が上昇することを明らかにしている。また二組並べて真空管内へ設置する新たな構成を提案し評価している。この成果は，太陽集熱器を実用化する上で重要な知見である。

第５章では，太陽集熱器の集熱効率の季節変動を評価している。太陽と太陽集熱器の位置関係を精密に評価しており，年平均の集熱量を評価した点が重要な成果である。

第６章では，太陽集熱器の集熱性能を実験により評価している。理論と実験値を比較し，良好な一致を得ている。この成果は理論モデルの妥当性を示した点で有益な成果である。

第７章では，太陽集熱器を利用した発電プラントを評価している。種々の冷媒を想定しランキンサイクルの熱効率を評価している。太陽集熱器を用いた発電について評価した点で重要な知見である。

第８章は結論である。

以上要するに本論文は，非結像集光器の基礎原理を利用して太陽集熱器への応用を行ったものであり，機械システムデザイン工学およびエネルギー工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。