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EXERGY EFFICIENCY FOR RADIATION HEAT TRANSFER

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ABSTRACT

One of the evaluation criteria for the performance of thermal processes is exergy analysis. Along with energy analysis, exergy calculations provide a clear and highly effective understanding of the performance of a system. Although exergy analysis has been extensively applied to many industrial processes, there are limited works for solar energy conversion systems that include the details of radiation transfer. The use of the Carnot efficiency expressions for calculating the exergy received from the thermal radiation source is questionable because it neglects the directional and spectral aspects of radiation heat transfer. In this study, the exergy efficiency calculations for radiation heat transfer in energy conversion systems are discussed. Comparisons of different expressions for exergy efficiency are presented, and the effects of source and sink temperature variations are explored.

INTRODUCTION

There are various approaches to specify the availability of solar energy which is based on the second law of thermodynamics and the entropy/exergy analysis [1-6]. However, exergy transfer by thermal radiation has still not been formulated, in detail and unambiguously, for complicated systems. Heat transfer textbooks usually take into account heat transfer by three modes: conduction, convection and radiation. But these procedures do not adapt into consideration exergy transfer from solar energy. The analysis of solar radiation by using the exergy approach has the potential to show how much energy can be converted to work effectively [7].

Petela [1] was one of the original researchers who outlined the formulation for the exergy of heat radiation. It was expressed that the ratio of exergy to energy from radiation is directly proportional to the exergy of a substance and its temperature. Also, the study briefly highlighted the potential applications of the impact of radiation energy on exergy analyses.

Parrott [2] presented the analytical upper bound expression for the efficiency of solar energy conversion. In this case, the theoretical expression for optimum useful work from solar energy was computed with respect to the directional solar radiation. Jeter [3] has demonstrated the optimal conversion of solar power and evaluated the performance. The solar radiation is assumed to be constant and the exergy of the systems was computed accordingly. Also showed that the steady flow rate was constrained by the constant temperature value used in the analysis.

When all the exergy is properly converted to work, it is possible to reverse the work flow, then, it is possible to obtain the optimum extraction work from the thermodynamic viewpoint. Gribik et al. [4] presented a controversial analysis for the second law of solar power conversion by concluding the correct expression resulting from Spanner. Based on this method, it was proposed a generalized thermodynamic expression. With the reflection taken into account, the fall in exergy efficiency due to the atmospheric scattering was also presented.

Wright et al. [5] presented a concise and simpler analysis of the problems to explain the concept of exergy analysis when dealing with thermodynamic systems where the radiative heat transfer is dominant through the use and proper application of the general exergy balance equation. The results show that Petela's thermodynamic approach, which is applicable for the exergy flux of blackbody radiation (BR), provides the upper bound performance for the conversion of solar radiation (SR) through (BR) estimation. Petela [6] also derived an expression for the study exergy of solar radiation for three groups and discussed the details. The formulation was improved for the understanding of exergy analysis of solar radiation and included the discussion of the formulas by the Petela, Spanner and Jeter with analysis of thermal radiation under specific conditions. Their proposed expressions relied on models that involved a system of radiating surfaces on which emission and absorption were occurring.

Hepbasli and Alsuhaibani [8] provided a review on the exergy of solar radiation by using several models and energy in various regions of Saudi Arabia and Turkey. The models by Petela, Spanner, and Jeter were adopted in their analysis. Nurullah [9] proposed three experimental approaches to obtain solar radiation exergy and compared with several statistical methods. The empirical enhancement model neglected Petela's expression. Saeed et al. [10] presented an artificial neural network (ANN) model for solar radiation and determined a work product from it. ANN results were compared with realistic data based on daily calculations. Their model is properly derived to validate the simulation results carried out in ANN. However, previous studies of the exergy analysis of the thermal radiation lack to consider a change of internal energy. In this study, it was provided a review of the previous works and outline an improved analysis including radiation heat transfer.

PROBLEM STATEMENT

This study focused on the question of how much work potential is available from thermal radiation transfer, and what fraction of it can be extracted as useful work. The first group of researchers [11–13] considered that exergy could be produced when solar energy was obtained in the form $Q(1-T_o/T)$. The second group [14,15] calculated solar radiation exergy that was available for a solar power plant in the mode $Q(1-4T_o/3T)$. Petela [1] gave an account stating the expression of the exergy can be obtained of blackbody radiation (BR). In the present study, the formulation exergy efficiency maximization is presented more directly and practically, the change in internal energy due to radiation transfer is also considered.

RESULTS AND DISCUSSION

Several models that comprise a cylinder–piston system have been used to analyze the maximum efficiency of solar radiation. However, concerns regarding the use of these models to verify the results arise because of uncertainties in their actual applications. Besides, the change in the internal energy of radiation should be considered. In this paper, considerable attention was given to the system that includes a radiation source and an absorbing sink at a constant volume. This system undergoes a reversible process from the initial state to the final state (dead state), including a change in internal energy. The exergy of the system, which can be produced from a change in internal energy and entropy, can be transformed into useful work. Maximum efficiency can be achieved, based on the definition of efficiency provided by the second law of thermodynamics. Thus, the development of this model is doubtless, and the result obtained using it can be considered for investigation. The ratio of thermal radiation exergy to thermal radiation energy is determined using the formulas presented in Table 1, and the results are compared in the following figures.

Table 1. Four formulations for maximum radiation efficiency presented by various researchers. [3,6,14,16].

Researcher	Input	Output	Maximum Efficiency
Petela	Radiation energy	Radiation exergy	$1+\frac{1}{3}\left(\frac{T_a}{T}\right)^4-\frac{4}{3}\frac{T_a}{T}$
Spanner	Radiation energy	Absolute work	$1-\frac{4}{3}\frac{T_a}{T}$
Jeter	Heat	Network of a heat engine	$1-\frac{T_a}{T}$
Present Approach Mohammed/Menguc	Radiation energy	Radiation exergy	$1-\frac{4}{3}\frac{\left(T_aT^3-T_a^4\right)}{\left(T^4-T_a^4\right)}$

All of the findings are focused on the ideal conversion of solar radiation into work. Although the use of several approaches is valid, doing so will prevent comparison with a perfect estimation of thermal radiation exergy. The difference between the formulas of Petela and Spanner emerges because Spanner's formula considers absolute work at maximum availability. The formula of Jeter is derived as the maximum efficiency result for the conversion of thermal radiation into work using Carnot efficiency and assuming that the surface of the sun and the surface of an environment are directly in contact.

For maximum efficiency, the values are calculated using the four expressions provided in Table 1, and the results are plotted in Figure 1. The variations between Jeter's maximum efficiency formula, which considers heat transfer via conduction and convection, and the other expressions, which consider heat transfer via radiation, are presented. It is clear that the maximum efficiency associated with radiation heat transfer is consistently less than the maximum efficiency related to conduction and convection heat transfer. That is, the losses caused by radiation heat transfer are higher than those caused by other modes of heat transfer because energy transfer via radiation is proportional to the fourth power of the temperature. For example, at a radiation temperature of 2000 K, the efficiency with radiation effect is less than 6.3% of the efficiency without radiation effect. As shown in Figure 1, the models proposed by Petela, Spanner, and the current study exhibit highly similar behavior because these approaches deal with the effect of radiation heat transfer. By contrast, Jeter's approach only focuses on conduction and convection heat transfer modes.

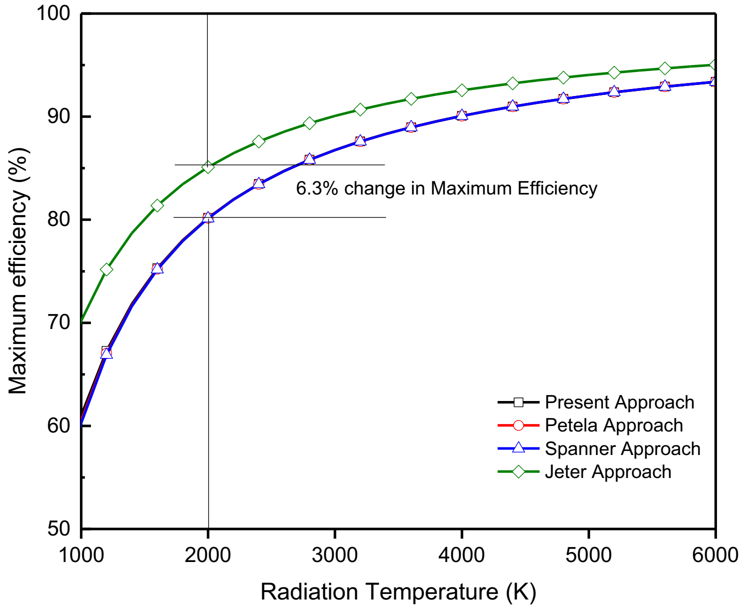

Figure 1. Results of the comparison of the maximum efficiency values of thermal radiation exergy.

Figure 2 shows the effect of environmental temperature on maximum efficiency. It is clear that an increase in ambient temperature reduces maximum efficiency. However, maximum efficiency is considerably increased when radiation temperature increases.

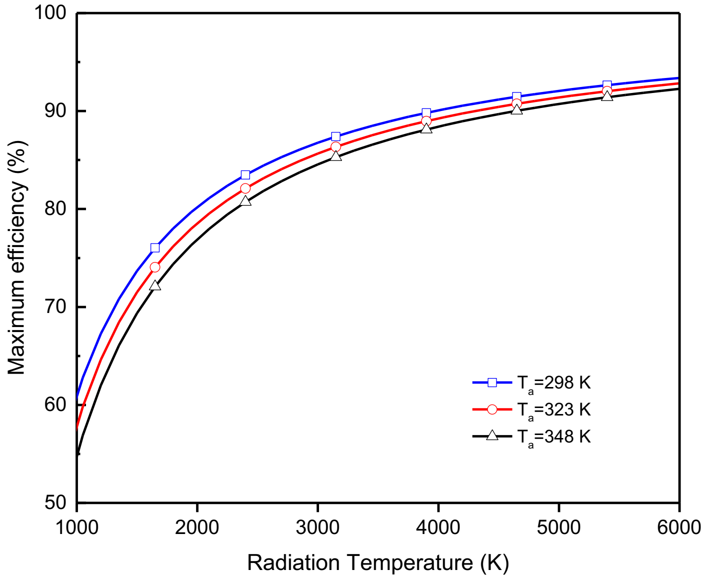

Figure 2. Effect of environmental temperature on maximum efficiency

The theoretical explanation for exergy destruction and maximum efficiency as a function of radiation temperature is shown in Figure 3.

Maximum efficiency increases exponentially from 60% at 1000 K to 85% at 2500 K. Then, it increases gradually until it reaches 93% at 6000 K. By contrast, exergy destruction decreases dramatically from 40% at 1000 K to 15% at 2500 K. Thereafter, it declines steadily to 7% at 6000 K. The maximum efficiency and exergy destruction exhibit dissimilar trends because a reduction in exergy destruction is considered as a gain in maximum efficiency.

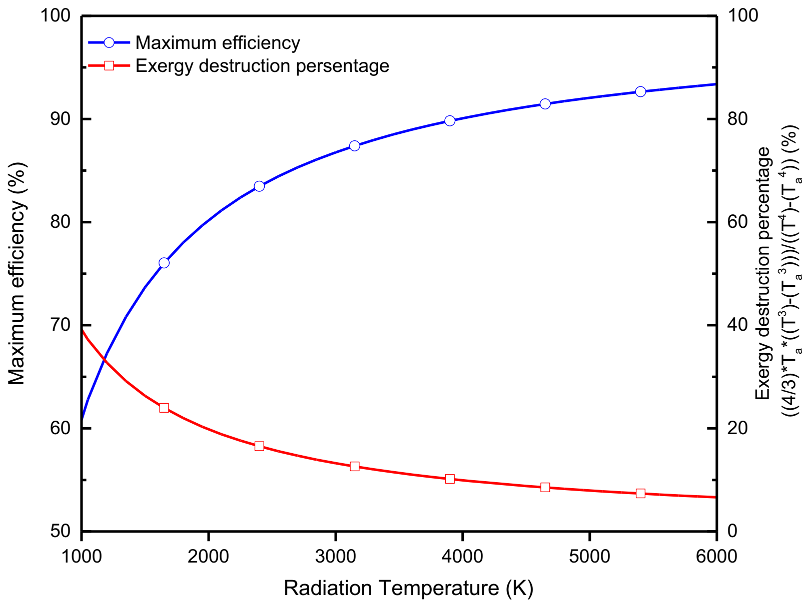

Figure 3. Effects of radiation temperature on maximum efficiency and exergy destruction.

CONCLUSIONS

In this paper, radiation transfer in exergy analysis was included in a more complete fashion. Although the current study is conducted under a different approach that considers constant volume, it still improves the concept of exergy analysis in a more fundamental way. The model deals with an enclosed system that comprises a radiation source and an absorbing sink. Such a system is more feasible than the system that involves a cylinder–piston unit. Comparisons with other studies show that the result obtained in the current formulation is similar to those of other approaches that involve thermal radiation. However, the present results suggest a less effective radiative transfer contribution than that of the approach that involves Carnot efficiency.

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Nomenclature

T	Solar temperature, K
T_a	Environmental temperature, K