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Entransy analysis of irreversible heat pump using Newton and Dulong–Petit heat transfer laws and relations with its performance

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ABSTRACT

An irreversible heat pump was investigated via entransy analysis and performance criteria. In the analyses, two different convective heat transfer laws were applied to the considered system: the Newton and Dulong–Petit heat transfer laws. The irreversibilities in the system are the result of a finite heat transfer rate, a heat leak and internal irreversibilities, including friction, turbulence etc. In this study, a thermodynamic analysis was performed in detail, and the numerical solutions were used for the conducted analysis. The maximum entransy dissipation (critical points) ranges from 18436.7 kW K to 18855.3 kW K according to *y* for Newton's law; however, there is no maximum point for the Dulon–Petit law. It can be concluded from this study that entransy should be used among the basic thermodynamic criteria.

1. Introduction

Studies on determining the most convenient conditions for thermodynamic cycles have been ongoing since Sadi Carnot proposed the famous Carnot cycle. Currently, environmental concerns are intensifying this process because more efficient cycles enable the release of a lower amount of carbon emissions into the atmosphere. Heat transfer processes are the most common physical phenomena in energy systems [1]. Due to the lack of a method to optimize the heat transfer process, Guo et al. proposed the entransy principle [2]. This principle, similar to entropy, is used for determining the irreversibilities resulting from the heat transfer process. Entransy is heat transfer potential and it is always destroyed during heat transfer. Entransy is described as follows according to Guo et al. [2]:

$$\dot{G} = \frac{1}{2}\dot{Q}T \qquad (1)$$

where $\dot{G}$ is the entransy flux (kW K), $\dot{Q}$ is the heat rate (kW) and T is the temperature (K). Because it provides new optimization potential, entransy should be among the investigated parameters when designing a thermodynamic cycle. Recent studies have been performed regarding the application of entransy in thermodynamic cycles [3–17].

Another important point regarding the design or evaluation of a thermodynamic cycle is the determination of the heat transfer effects on the cycle. Many papers in the literature considered the effect of heat transfer on different cycles, including heat pumps, refrigerator cycles and heat engines [18–55].

In this study, the entransy parameters and the performance evaluation of an irreversible heat pump cycle were combined and the influence of the two heat transfer laws on the entransy was investigated. One these laws is the Newton heat transfer law, which regards only the connective part of the heat transfer, and the other law is the Dulong–Petit law, which includes the conductive and radiative parts of the heat transfer in addition to the connective part [56–58]. Entransy analysis using different heat transfer laws is applied to a totally irreversible heat pump for the first time. In addition, this analysis is compared with other thermodynamic performance criteria and entransy is offered as a basic thermodynamic performance criteria.

2. System description and thermodynamic analysis

In thermodynamics, the upper limits of a heat pump are defined using a Carnot heat-pump model. The work from a Carnot heat pump system is obtained from the environment and transferred to the machine via the transfer heat from a low temperature heat

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Nomenclature

c	heat conductance for the heat leak (kW/K)
COP	coefficient of performance
$\dot{G}$	entransy (kW K)
I	internal irreversibility parameter
k	heat conductance (kW/K)
q	heat leak (kW)
$\dot{Q}$	heat (kW)
T	temperature (K)
S	entropy (kW/K)
$\dot{W}$	power (kW)
x	ratio of heats
y	ratio of the heat conductances
z	sum of the heat conductances

Subscripts

o	environment
C	condenser
d	dissipation
E	evaporator
gen	generation
H	high
L	low
lk	leak
R	reversible
w	work

Greek letters

γ	entransy efficiency
φ	exergy efficiency

source to a high temperature heat sink. Hence, a heat pump can be used for space heating. A Carnot heat pump does not include irreversibility, so it is assumed to be reversible. Therefore, a Carnot heat pump exhibits the minimum work input and the maximum COP (coefficient of performance). Thus, a Carnot heat pump can be described as the most efficient heat-pump cycle. However, reversible cycles cannot exist in reality. For this reason, an irreversible heat pump cycle must be developed. Irreversibilities in the heat pump result from heat leaks, internal irreversibilities and a finite heat transfer rate. The irreversible heat pump investigated in this study is shown in Fig. 1. The assumptions made in the thermodynamic analyses of this study are as follows:

- The system operates under steady state conditions.
- All of the processes are irreversible.
- The environmental conditions are $T_o = 298.15$ K and $P_o = 100$ kPa.

The thermodynamic analyses of an entransy analysis, determining the amount of entropy generation and evaluation of the performance criteria were conducted and their effects on the systems were researched. The optimum parameters studied in this paper are the temperature ratio and the heat conductance ratio. These parameters have significant effects on the system and, therefore, are important design parameters. The thermodynamic analysis methods developed by Li et al. [41,43] and Chen et al. [59] were used in this study. A flow chart of the method is illustrated in Fig. 2.

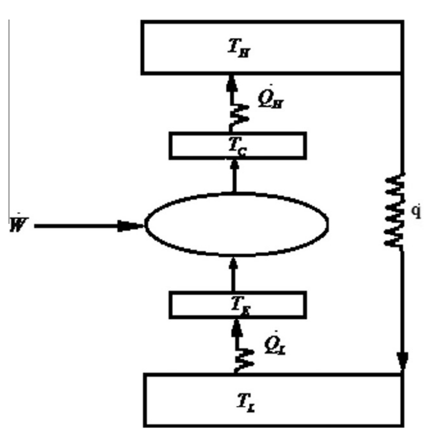

Fig. 1. Schematic of the irreversible heat pump.

The heat absorbed by the system and the heat rejected from the system are described in Eqs. (2) and (3), respectively:

$$\dot{Q}_H = k_C(T_C - T_H)^n \tag{2}$$

$$\dot{Q}_L = k_E(T_L - T_E)^n \tag{3}$$

where the $n = 1$ heat transfer law is called the Newton heat transfer law, while the $n = 1.25$ heat transfer law is called the Dulong–Petit law [50–52]. Heat leaks from the system to the environment are described by:

$$\dot{q} = c(T_H - T_L)^n \tag{4}$$

The dimensionless temperature ratio of the condenser and the evaporator is described by Eq. (5):

$$x = \frac{T_C}{T_E} \tag{5}$$

The dimensionless heat conductance ratio of the condenser and the evaporator is given by Eq. (6):

$$y = \frac{k_C}{k_E} \tag{6}$$

The sum of the heat conductance of the condenser and evaporator can be defined as follows:

$$z = k_C + k_E \tag{7}$$

The first law of thermodynamics dictates that Eq. (8) applies to the system:

$$\dot{W} = \dot{Q}_H - \dot{Q}_L \tag{8}$$

From the Clausius equations, the internal irreversibility parameter (I) and the entropy generation of the system can be written as Eqs. (9) and (10), respectively:

$$\frac{\dot{Q}_H}{T_C} = I\frac{\dot{Q}_L}{T_E} \quad \text{or} \quad I = \frac{\Delta S_C}{\Delta S_E} \tag{9}$$

$$S_{gen} = \left(\frac{\dot{Q}_H}{T_H} - \frac{\dot{Q}_L}{T_L}\right) + \dot{q}\left(\frac{1}{T_L} - \frac{1}{T_H}\right) \tag{10}$$

The COP of the irreversible heat pump is: