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# Second law thermodynamic study of heat exchangers: A review

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ABSTRACT

Heat exchangers are thermal systems which are used extensively, have a major role in energy conservation aspect and preventing global warming. This paper is based on reviews of scientific work and provides a state-of-the-art review of second law of thermodynamic analysis of heat exchangers. Initially, the basics of heat exchangers are briefly provided along with second law analysis which also includes two-phase flow analysis and thermoeconomic analysis. Following this, detail literature survey based on performance parameters such as entropy generation, exergy analysis, production and manufacturing irreversibilities (cumulative exergy destruction associated with the production of material and manufacturing of component or assembly of components) and two phase fluid loss of heat exchangers is presented including constructal law applied to analyze heat exchangers. Constructal theory along with second law analysis can be used for the systematic design of heat exchangers. This review highlights the importance of first and second law investigations of heat exchangers leading to energy conservation.



**Contents**



## 1. Introduction

Energy conservation is key goal of the world economy and will continue to be one in the future. The most effective way to reduce energy demand is to use energy more efficiently. Heat exchangers are widely used in power engineering, chemical industries, petroleum refineries, food industries and in *HVAC* (heating, ventilating and air conditioning) technology. Therefore, heat transfer and the design of heat transfer equipment continue to be a centrally important issue in energy conservation. The optimal use of energy and efficient heat transfer has become a vital importance as a result of the diminishing world energy resources and increasing energy cost. Therefore, the number of investigations on heat transfer enhancement has progressively increased. As a result, it is very important to determine the performance of

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**Nomenclature**

| | |
|---|---|
| $A$ | surface area, m$^2$ |
| $Be$ | Bejan number |
| $C$ | heat capcity rate, W/K |
| $c$ | specific heat, J/kg K |
| $c_p$ | specific heat at constant pressure, J/kg K |
| $c_v$ | specific heat at constant volume, J/kg K |
| $C_r$ | capacity ratio |
| $D$ | diameter, m |
| $\dot{E}$ | exergy rate, W |
| $E_{vh}$ | entransy, J K |
| $h$ | specific enthalpy, J/kg |
| $EEIN$ | enthalpy exchange irreversibility norm |
| $HVAC$ | heating, ventilating and air conditioning |
| $\dot{I}$ | irreversibility, W |
| $k$ | thermal conductivity, W/m K |
| $L$ | length, m |
| $\dot{m}$ | mass flow rate, kg/s |
| $M$ | mass, kg |
| $n$ | number of constructal level |
| $Ntu$ | number of heat transfer units |
| $P$ | pressure, Pa |
| $\Delta P$ | pressure drop, Pa |
| $Q$ | heat transfer, J |
| $\dot{Q}$ | heat transfer rate, W |
| $R$ | gas constant, J/kg K |
| $s$ | specific entropy, J/kg K |
| $S$ | entropy, J/K |
| $\dot{S}_{gen}$ | entropy generation rate, W/K |
| $Sv$ | svelteness |
| $T$ | temperature, K |
| $\Delta T$ | temperature difference, K |
| $T_o$ | reference temperature, K |
| $u$ | specific internal energy, J/kg |
| $U$ | overall heat transfer coefficient, W/m$^2$ K |
| $\dot{W}$ | Work, W |
| $Y_S$ | Heat Exchange Reversibility Norm (HERN) |

*Greek symbols*

| | |
|---|---|
| $\varepsilon$ | effectiveness |
| $\rho$ | density, kg/ m$^3$ |
| $\upsilon$ | kinematic viscosity, m$^2$/s |
| $\psi$ | rational efficiency |

*Subscripts*

| | |
|---|---|
| 1 | stream 1 |
| 2 | stream 2 |
| $c$ | cold stream |
| $h$ | hot stream |
| $H$ | heat transfer term |
| $in$ | inlet |
| $m$ | material |
| $max$ | maximum |
| $min$ | minimum |
| $out$ | outlet |
| $P$ | pressure drop term |
| $sat$ | saturated condition |
| $tp$ | two-phase |
| $v$ | vapor |

heat exchange devices on both heat transfer and thermodynamic considerations. Heat exchangers are the equipments that provide the flow of thermal energy between two or more fluids at different temperatures. Heat exchangers are used in variety of applications. There are four basic types of losses that occur in a typical heat exchanger as referred from Bejan [1–6]:

(i) losses due to the exchange of heat across a finite temperature difference,
(ii) losses due to fluid friction,
(iii) losses due to material and manufacturing of heat exchanger [7], and
(iv) thermal losses due to heat exchange with the environment.

The last heat exchanger losses are usually small, because the heat exchanger surface is insulated to reduce such an exchange of heat. Other losses are evaluated using thermodynamic analysis of heat exchangers. The first law of thermodynamics deals with the quantitative conservation of energy in various forms transferred between the system and its surroundings and with the changes in the energy stored in the system. It treats work and heat interactions as equivalent form of energy in transit. It deals with the quantity of energy and asserts that energy cannot be created or destroyed. The second law however, deals with the quality of energy. More specifically, it is concerned with the degradation of energy during a process, the entropy generation and lost opportunities to do work. The second law of thermodynamics has proved to be a very powerful tool in the optimization of complex thermodynamic systems and is required to establish the difference in quality between mechanical and thermal energy [8].

A reversible process is defined as a process that can be reversed without leaving any trace on the surroundings. Processes that are not reversible are called irreversible processes. The factors that cause a process to be irreversible are called irreversibilities. They include heat transfer across a finite temperature difference, friction, unrestrained expansion, mixing of fluids, etc. The irreversiblities occurring during a process is called process irreversibility. Entropy is defined as a system property by a statement that its change in an ideal, reversible process must be equal to the transfer of an entity $\int dQ/T$ that accompanies any heat transfer $dQ$ across the system boundary where the local temperature is $T$. Hence, this abstract system property indicates that heat transfer must be accompanied by an entropy change. As a consequence, a reversible adiabatic process can be identified by zero entropy change. If a process is not reversible (as with any heat transfer across a finite temperature difference), the situation is radically different. Entropy change $\Delta S$ is either equal (reversible process) or larger (irreversible process) than the entropy transfer ($\int dQ/T$) that accompanies heat transfer $dQ$, the difference being attributed to entropy generation $\dot{S}_{gen}$. The amount of entropy generation is the quantitative measure of the quality level of energy transfer. Entropy generation of zero corresponds to the highest quality of energy transfer and/or energy conversion (a reversible process), and entropy generation greater than zero represents poorer quality. All real processes are characterized by entropy generation greater than zero. Irreversibility can be expressed in energy terms as a product of entropy generation and a reference temperature, $T_o$ (i.e., $\dot{I}=T_o\dot{S}_{gen}$).

Heat exchangers are generally inefficient from an energy conservation point of view because they have been designed in