Common Theoretical Foundation of Thermodynamics and Heat Transfer: Universal Exergy Equation for Reversible and Irreversible Processes Postprint

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Date: 2017-10-30T00:00:00+00:00

Abstract

This study reviews and summarizes a series of research achievements on the common theoretical foundation of thermodynamics and heat transfer. Beginning with an examination of the practical application issues concerning the second law of thermodynamics and "entropy generation" theory, and based on potential energy theory, exergy and anergy within energy are defined using the potential energy relative to the environmental equilibrium state as the reference potential energy. This definition not only shares the same properties as "?" but also enables the direct formulation of exergy function expressions from its defining equation. Subsequently, by utilizing the first law of thermodynamics equation, universal exergy equations and exergy rate equations are derived, which are then compared with entropy equations, entransy dissipation equations, and ? equations. The terms in the former equations are all state-dependent and can be calculated independently, whereas the latter three equations each contain a complementary term related to irreversible processes. The application of the exergy rate equation to heat transfer processes yields expressions for heat transfer efficiency; when applied to actual heat engine systems, it derives the relationships between output power, input heat flow rate, efficiency, heat exchanger heat transfer coefficient, and heat source parameters in coupled heat transfer and thermodynamic systems, with examples provided for system optimization design. The common theoretical framework for thermodynamics and heat transfer constructed in this paper provides a theoretical foundation for the comprehensive analysis and coordinated optimization of thermodynamic systems coupling heat engines and heat exchangers.

Full Text

1. Introduction

The foundation of modern thermodynamics rests upon Clausius' s inequality, which states that for any thermodynamic process, the change in entropy dS satisfies dS Q/T, where Q is the heat transfer and T is the absolute temperature. This principle establishes that the total entropy change comprises two components: entropy flow dSf = Q/T and entropy generation dSg, giving the fundamental relation dS = dSf + dSg. For isolated systems, this leads to the second law statement dS_iso > 0, where entropy generation is always positive for irreversible processes.

Building upon these principles, the concept of effective energy (exergy) emerges as a crucial metric for quantifying the maximum useful work obtainable from a system interacting with its environment. Following Rant's terminology, the total energy E can be decomposed into effective energy (exergy) and ineffective energy (anergy). The maximum work potential is determined by the state difference between the system and its environment reference state (T0, p0).

2. Effective Energy Analysis

The maximum useful work from a system is given by:

$$W_{\max} = (U - T_0 S + p_0 V) - (U_0 - T_0 S_0 + p_0 V_0)$$

where U, S, and V represent the internal energy, entropy, and volume of the system, respectively, and the subscript 0 denotes environmental reference conditions. This expression reveals that not all energy is available for work; only the portion above the environmental datum can be converted.

The effective energy equation can be expressed in differential form as:

$$dE = dE_u + dE_n$$

where dEu represents the available portion and dEn the unavailable portion. For heat transfer processes, the thermal exergy is:

$$E_{u,T} = (T - T_0)S = \left(1 - \frac{T_0}{T}\right) Q$$

Similarly, for pressure-volume work:

$$E_{u,p} = (p - p_0)V$$

The exergy balance for any process follows:

$$E_{x,in} = E_{x,out} + \Delta E_{x,f} + E_{x,ir}$$

where $E_{x,ir}$ represents exergy destruction due to irreversibilities, directly related to entropy generation.

3. Endoreversible Carnot Cycle Analysis

For a Carnot heat engine operating between thermal reservoirs at temperatures TH (hot) and TL (cold), the endoreversible model accounts for finite-rate heat transfer while maintaining internal reversibility. The working fluid temperatures at the hot and cold sides are T1 and T2, respectively, with T1 < TH and T2 > TL due to thermal resistance.

The power output and efficiency are given by:

$$P = \frac{Q_H - Q_L}{t_{cycle}}$$

where the heat transfers follow Newton’ s law:

$$Q_H = \alpha(T_H - T_1)t_H$$

$$Q_L = \beta(T_2 - T_L)t_L$$

The entropy balance for the endoreversible cycle requires:

$$\frac{Q_H}{T_1} = \frac{Q_L}{T_2}$$

4. Maximum Power Efficiency

Optimizing the power output with respect to the temperature ratio yields the Curzon-Ahlborn efficiency at maximum power:

$$\eta_{CA} = 1 - \sqrt{\frac{T_L}{T_H}}$$

This result emerges from solving dP/dT2 = 0, giving the optimal intermediate temperature:

$$T_{2,m} = T_L + \sqrt{\frac{T_H T_L}{1+\tau}}$$

where represents the ratio of heat transfer coefficients. The corresponding maximum power is:

$$P_{\max} = \frac{\alpha}{1+\tau}\left(\sqrt{T_H} - \sqrt{T_L}\right)^2$$

The efficiency at maximum power can be expressed as:

$$\eta_{opt} = \frac{1 - \sqrt{T_L/T_H}}{1 + \sqrt{T_L/T_H}}$$

5. Performance Characteristics

[Figure 2: see original paper] shows the actual overheating Rankine cycle performance, while [Figure 3: see original paper] presents the temperature-entropy diagram for the endoreversible Carnot cycle. The dimensionless power output Pr = P/P_max varies with the temperature ratio and the reservoir temperature ratio TL/TH.

For TH = 1000 K and TL = 300 K, the Carnot efficiency would be 70%, while the Curzon-Ahlborn efficiency at maximum power is approximately 45%. The analysis demonstrates that practical heat engines must balance efficiency and power output, with the endoreversible model providing realistic bounds between the ideal Carnot limit and actual performance.

The relationship between optimal efficiency and power output follows a characteristic curve where efficiency initially increases with power, reaches a maximum, then decreases as irreversibilities dominate at high power outputs. This trade-off is fundamental to finite-time thermodynamics and engineering design of thermal systems.

Note: Figure translations are in progress. See original paper for figures.

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