



ENERGY-EXERGY ANALYSIS VERSUS ENERGY, EXERGY AND THERMOECONOMIC ANALYSIS – A CASE OF STUDY

Feiza MEMET¹

¹Constanta Maritime University, Faculty of Naval Electro-Mechanics, 104 Mircea cel Batran Street, 900663, Constanta, Romania, ORCID ID:0000-0002-3110-4254, feizamemet@yahoo.com

Abstract: On board of ships, cascade refrigeration systems are used when both frozen and refrigerated products are transported. In such a situation, two different levels of temperature are ensured in the same time. There are needed two conventional refrigeration systems which are coupled by a cascade heat exchanger. Thermodynamic analysis of these systems are important when aiming efficient design and performance optimization. The main objective of this paper is to present different analysis means such as energy, exergy or thermoeconomic (exergoeconomic). Also, there are analysed the challenges to be faced by engineers when developing a thermoeconomic analysis of cascade vapour compression refrigeration systems. Thermoeconomics analysis is a “sensitive issue” due to the interdisciplinary approach, being combined concepts of economics and thermodynamics to evaluate cost formation process of these thermal systems.

Key words: analysis, cascade, exergoeconomy, refrigeration.

1. INTRODUCTION

Refrigeration relies on the first and second laws of thermodynamics, its goal being heat remove from a cold space to a higher temperature environment; this process is not a spontaneous one, being needed work input and phase changes of the working fluid (the refrigerant); this sector is growing rapidly and impacts areas such as: air conditioning, preservation and transportation of perishables, food processing, storing, etc [1].

Vapour compression refrigeration systems are commonly used in many refrigeration areas, including marine refrigeration. High demand regarding this industry rised challenges seeing important energy consumption amounts. For this reason, the optimization of these cycles is of a high importance. Because these systems are designed to work in optimum conditions, it is aimed the economical operation regime.

On board ships, cascade refrigeration systems are used when both frozen and refrigerated products are transported, in which case two different temperature levels must be ensured simultaneously. This system is obtained by coupling two conventional refrigeration systems. This coupling is made possible by a dual purpose heat exchanger (cascade heat exchanger). This heat exchanger plays the role of condenser for one of the conventional systems and the role of evaporator for the second system. Two different refrigerants circulate through the two traditional systems. These, having

different thermodynamic properties, allow different temperature levels to be ensured during the voyage.

This paper deals with energy, exergy and thermoeconomic (exergoeconomic) analysis aspects of a cascade refrigeration system.

Exergy analysis, which is based on the first law of thermodynamics provides theoretical information on estimation of energy demands.

But the reality of practical settings is associated with the irreversibility of real processes. This is why both quantity and quality aspects of energy should be addressed in order to get a realistic perspective on the performance.

The solution is found in the use of exergy analysis which allows the understanding of energy losses by pointing out the sites of irreversible losses.

Moving forward, joining energy and exergy analysis with thermoeconomic analysis it is possible to achieve a comprehensive evaluation and optimization of the cascade refrigeration system.

Thermoeconomics is a new multidisciplinary field, suitable for the design optimization and diagnosis of energy systems which combines thermodynamic and economic analysis, by considering both efficiency and costs from second law perspective. According to Valero et al [2] and [3], exergy (which is introduced by the second law) is very suitable to allocate costs.

The exergy balance (eq. 1) quantifies the degradation of exergy and refers to the assessment of the useful energy inside a system.



$$Ex_i - Ex_o = I > 0 \quad (1)$$

where:

Ex_i – exergy input,
 Ex_o – exergy output,
 I – irreversibilities.

Seeing that the objective of a process is its efficiency, the following equation puts the efficiency expressed by concepts defined in the field of economics; these are the product and the resource.

$$\text{efficiency} = P/F \quad (2)$$

where:

P – product,
 F – resource.

From this perspective, it is possible to write eq. 3 as:

$$F - P = R + I > 0 \quad (3)$$

where:

R – residues.

Another goal of this paper is to provide a descriptive overview of the engineering challenges faced by the specialists when dealing with economic aspects to be introduced in an exergoeconomic analysis of a cascade vapour compression refrigeration system.

2. SYSTEM DESCRIPTION AND ENERGY, EXERGY AND THERMOECONOMIC ANALYSIS EQUATIONS

Figure 1 provides the schematic layout of the considered system. As mentioned above, there are two classic vapour compression refrigeration systems: a low temperature circuit – LTC and a high temperature circuit – HTC, connected in series by the use a cascade condenser (CC). The cascade condenser acts as a condenser for the LTC and as an evaporator for the HTC.

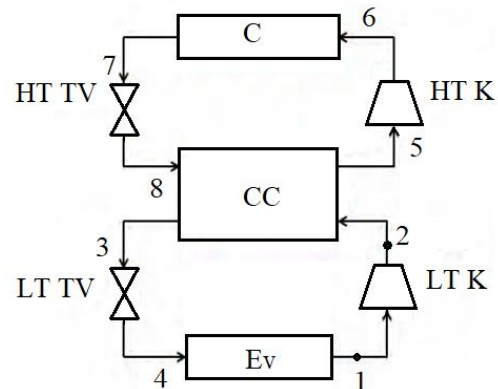


Figure 1 Cascade refrigeration system:
K – compressor, C – condenser, TV – throttling valve, Ev - evaporator

Energy analysis: the modelling is provided below [4], [5] as:

For the HTC:

$$\dot{m}_{\text{HTC}} = \frac{\dot{Q}_{\text{CC}}}{h_5 - h_8} \quad (4)$$

$$\dot{W}_{\text{HTC}} = \frac{\dot{m}_{\text{HTC}}(h_6 - h_5)}{\eta_{\text{C,H}}} \quad (5)$$

$$\dot{Q}_{\text{C}} = \dot{m}_{\text{HTC}}(h_6 - h_7) \quad (6)$$

For the LTC:

$$\dot{m}_{\text{LTC}} = \frac{\dot{Q}_{\text{Ev}}}{h_1 - h_4} \quad (7)$$

$$\dot{W}_{\text{LTC}} = \frac{\dot{m}_{\text{LTC}}(h_2 - h_1)}{\eta_{\text{C,L}}} \quad (8)$$

For all the system:

$$\text{COP} = \frac{\dot{Q}_{\text{Ev}}}{\dot{W}_{\text{HTC}} + \dot{W}_{\text{LTC}}} \quad (9)$$

Since there are three heat exchangers in the analysed system, the following equations are introduced:

$$\dot{Q} = U \cdot A \cdot \text{LMTD} \quad (10)$$

$$\text{LMTD} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln \frac{(T_{h,i} - T_{c,o})}{(T_{h,o} - T_{c,i})}} \quad (11)$$

where:

\dot{m} – refrigerant mass flow rate, kg/s,

\dot{W} – power input, W,

h – specific enthalpy, J/kg,

\dot{Q} – heat flux, W,

η_c – isentropic efficiency of the compressor,

COP – Coefficient of Performance,

U – overall heat transfer coefficient of the heat exchanger, W/m²K,

A – heat transfer surface, m²,

LMTD – logarithmic mean temperature difference between two refrigerants,

T – temperature, K,

h/c – hot/cold,

i/o – inlet/outlet.

Exergy analysis: the modelling is provided below [6] as:

For the HTC:

$$\dot{E}x_{D,HTC} = \dot{W}_{HTC} + \dot{E}x_6 - \dot{E}x_5 \quad (12)$$

$$\dot{E}x_{D,C} = \dot{E}x_7 - \dot{E}x_6 \quad (13)$$

$$\dot{E}x_{D,HTTV} = \dot{E}x_8 - \dot{E}x_7 \quad (14)$$

$$\dot{E}x_{D,CC} = (\dot{E}x_8 - \dot{E}x_5) - (\dot{E}x_3 - \dot{E}x_2) \quad (15)$$

For the LTC:

$$\dot{E}x_{D,LTC} = \dot{W}_{LTC} + \dot{E}x_2 - \dot{E}x_1 \quad (16)$$

$$\dot{E}x_{D,Ev} = \dot{E}x_4 - \dot{E}x_1 \quad (17)$$

$$\dot{E}x_{D,LTTV} = \dot{E}x_4 - \dot{E}x_3 \quad (18)$$

$$\begin{aligned} \dot{E}x_{D,TOT} &= \dot{E}x_{D,HTC} + \dot{E}x_{D,C} + \dot{E}x_{D,HTTV} + \\ &+ \dot{E}x_{D,CC} + \dot{E}x_{D,LTC} + \dot{E}x_{D,Ev} + \dot{E}x_{D,LTTV} \end{aligned} \quad (19)$$

$$\eta_{ex} = \frac{(\dot{W}_{HTC} + \dot{W}_{LTC}) - \dot{E}x_{D,TOT}}{\dot{W}_{HTC} + \dot{W}_{LTC}} \quad (20)$$

where:

$\dot{E}x_D$ – exergy destruction, W,

$\dot{E}x$ – exergy, W,

η_{ex} – exergy efficiency.

Thermoeconomic analysis: the modelling is provided below [7], [8], [9], [10], [11] as:

Cost and price are different economic concepts. While cost is the amount of resources incurred in obtaining a product, price is the payment need for the acquiring of the product.

Cost estimation depends on policies and price estimation is done through facts. Processes to generate products are irreversible.

Since when exergy was proposed (as an energy term) to be related to cost, resulted a new analysis method (also known as exergoeconomic) suitable to be used in thermal systems optimization with a correctness not achievable by traditional methods.

Between price and worth can be establish a similitude.

Assessing an asset's worth involves a personal view– when it is about its estimation

The total capital investment of the cascade refrigeration system (\dot{Z}_{system}) and the capital investment cost rate of the k-th component of the system (\dot{Z}_k) are found by the use of the following formulae.

$$\dot{Z}_{system} = \sum_k \dot{Z}_k + \dot{Z}_{OPS} + \dot{Z}_{env} \quad (21)$$

where:

\dot{Z}_{OPS} – operational cost of the system,

\dot{Z}_{env} – environmental cost.

$$\dot{Z}_k = Z_k \cdot \Phi \cdot \text{CRF} \quad (22)$$

where:

Z_k – capital cost function,

Φ – maintenance factor,

CRF – capital recovery factor.

For the evaporator:

$$Z_{ev} = 1397 \cdot A_{ev}^{0.89} \quad (23)$$

For the condenser:

$$Z_C = 1397 \cdot A_C^{0.89} \quad (24)$$

For the cascade condenser:

$$Z_{CC} = 383.5 \cdot A_{CC}^{0.65} \quad (25)$$

For the HTC:

$$Z_{HTC} = 9624.2 \cdot W_{HTC}^{0.46} \quad (26)$$

For the LTC:

$$Z_{LTC} = 10167.5 \cdot W_{LTC}^{0.46} \quad (27)$$

For the HTTV:

$$Z_{HTTV} = 114.5 \cdot \dot{m}_{HTC} \quad (28)$$

For the LTTV:

$$Z_{LTTV} = 114.5 \cdot \dot{m}_{LTC} \quad (29)$$

$$CRF = \frac{(i+1)^n}{(i+1)^n - 1} \quad (30)$$

where:

i – annual time interest rate,

n – life time of the system.

$$\dot{Z}_{OPS} = A_h \cdot (W_{HTC} + W_{LTC}) \cdot Z_{elec} \quad (31)$$

where:

A_h – annual operational time (in hours),

Z_{elec} – cost of electricity.

$$\dot{Z}_{env} = \dot{m}_{CO_2} \cdot Z_{CO_2} \quad (32)$$

where:

\dot{m}_{CO_2} – amount of greenhouse gas emissions released by

the cascade vapour compression system,

Z_{CO_2} – the cost of CO_2 .

$$\dot{m}_{CO_2} = \lambda (\dot{W}_{HTC} + \dot{W}_{LTC}) \quad (33)$$

where:

λ – emission conversion factor, kg/kWh.

3. ENGINEERING CHALLENGES

Below are given identified challenges for engineers when introducing economic knowledge into cascade vapour compression refrigeration system (CVCRS) analysis within a thermoeconomic (exergo economic) approach.

A. The challenge of cost function accuracy – while conventional exergy analysis equations are governed by physical constants, thermoeconomic is ruled by cost functions; these are known to be difficult to be defined with precision for the vapour compression cascade systems.

Examples of non-linear equipment cost are the cost of compressors or heat exchangers, which do not scale linearly with size, making engineers to work with specific power law equations.

There are also material constraints, since these systems might work at very low temperatures, while the two circuits of the system require for different material.

Engineers might be in difficulty when estimating the cost of specialized low temperature steels or alloys, without a specific training.

B. Temporal and macroeconomic volatility – within an energy analysis, the performance of the CVCRS is given by COP, which is constant for specific working input data.

Instead, thermoeconomic analysis reflects specific economic conjuncture.

It is important to pay attention to energy tariffs dynamism, seen that compressors are high energy consumers and the tariff for electricity depends on different factors, such as: hour of day, season, region, etc.

On the other hand, considering the lifetime of the system, it is obvious the need to predict interest rates and inflation.

A slightly change in borrowing costs can put pressure on a business decision, such as choosing between an expensive, energy-efficient system and a cheaper, less efficient one.

The initial decision might favour the high-efficiency option due to long-term savings, but if interest rates rise even gently, the increased cost of the initial investment makes the low-cost option more financially attractive.

C. The “cost allocation” uncertainty

As shown above, in CVCRS the cascade condenser plays two roles: one of condenser for the LTC and of evaporator for the HTC, resulting a systemic challenge from thermoeconomic point of view.

Specialists have to answer to the question: “how should be allocated the cost for exergy destruction in this heat exchanger?”.

Engineers have to choose between two options: irreversibilities should be charge to the product (meaning the cooling at LTC evaporator) or should be shared between the two circuits.

Also, there is a recurrent costing, since the output of a cycle is the input for the second one.

In order to be solved the specific cost balance equations, are needed skills in matrix algebra that overpass the lacking between economics and thermodynamics.

D. Multi-objective optimization conflicts – resulting from antagonist position of thermodynamic perspective and economic profit.



It is needed the use of the exergoeconomic factor, that is able to reveal to engineers if the cost of the system is subjected by the initial purchase price or the operational inefficiency.

In the case of low values of this factor, specialists should be aware that they have to buy a more performant equipment.

Also, nowadays engineers have to pay attention to environmental regulations. Thus, they must consider the exergoenvironmental costs, such as carbon taxes or refrigerant GWP penalties. They must incorporate variable environmental compliance costs alongside total annual costs, that introduces a significant new dimension to financial modelling.

4. CONCLUSIONS

The main conclusions are given below:

- energy analysis offers limited outcomes since it provides theoretical information on estimation of energy demands,
- exergy analysis permits the understanding of energy losses, being able to indicate the sites of irreversible losses,
- exergoeconomic (thermoeconomic) analysis establishes a link between identification and quantification of irreversibilities and costs,
- for engineers, thermoeconomics is a delicate mission, they having to handle with the challenge of cost function accuracy, temporal and macroeconomic volatility, “cost allocation” uncertainty and multi-objective optimization conflicts.

5. CREDit Authors Statement

Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing: M. F.

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