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# An equivalent temperature based approach for selection of the most appropriate working fluids for refrigeration cycles

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ABSTRACT

This article presents a novel comprehensive approach for the selection of the most appropriate working fluids and the conceptual design of vapor-compression refrigeration cycles, subject to minimal overall conductance for fixed cooling capacity with fixed temperatures of the external fluids entering the condenser and the evaporator. The approach consists of three sequential steps: the first step is the refrigerant independent calculation of the minimum thermal conductance of the system via constrained optimization. The second law analysis constrains the optimization problem where some thermodynamic considerations of *h-s* diagram and equivalent temperature concept provide the ability to calculate the entropy generation in each component of the system. The optimization results establish thermodynamic criteria for the pre-selection of potential refrigerants. Since the optimum conditions obtained are expressed in terms of equivalent temperatures, in the second step, a reconstruction procedure is introduced to correlate the equivalent temperatures with the essential thermodynamic characteristics of the system such as working pressures, temperatures, and mass flow rate for each pre-selected refrigerant. The last step of the approach is the final selection of the optimal refrigerant among the candidates using a capital-operating cost performance criterion. A case study was presented to illustrate the application of the novel selection approach.

## 1. Introduction

The vapor-compression refrigeration cycle is the most widely used technology for the production of cold in residential, commercial and industrial applications [1]. Nowadays, in the context of the rapid growth of energy demand and cost, the optimization of such cycles has drawn much attention from researchers. The economic, environmental and operating performance of a refrigeration cycle depends heavily on the selection of the working fluid [2,3], as well as the design [4,5] and operating characteristics of the cycle [6,7].

Thermodynamic optimization models for the vapor-compression cycles can be categorized into empirical and theoretical groups. The former may contain several empirical coefficients, which typically are refrigerant-based [8,9]. Due to the very large and increasing number of working fluids, the most appropriate working fluid corresponding to given conditions of external reservoirs needs to be selected based on systematic approach. Thus, the application of the empirical model in a systematic selection of the optimal working fluid, which necessitates having a huge volume of data, will be unattainable. In this case, the alternative group, based on theoretical models [10], which are independent of the working fluid, will be very desirable. Theoretical model can provide preliminary design of the system based on the availability of the heat reservoirs, without the detailed characteristics of the system components. The main objective of a theoretical model is to calculate the optimal operating conditions of the system such as condensation and evaporation temperatures without recourse to the knowledge of working fluids and their thermo-physical properties. Several attempts have been made to develop the theoretical model by various endoreversible Carnot refrigerators using finite-time thermodynamics, which comprises external irreversibility associated with finite temperature-difference heat transfer [11,12]. The endoreversible model does not account for internal irreversible processes. In order to deal with the internal losses, researchers considered the generic source of internal irreversibility by a dimensionless numerical coefficient using Clausius inequality and minimized the thermal conductance of the system for a fixed cooling capacity or maximized the cooling capacity for a constant overall thermal conductance [13–15]. It should be noted that although this generic coefficient paves the way for the development of the system design, its value has been selected arbitrarily and independently of the operating conditions, thus it can prevent precise

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**Nomenclature**

| | |
|---|---|
| $COP$ | coefficient of performance |
| $ds$ | entropy difference (kJ/kg K) |
| $dh$ | enthalpy difference (kJ/kg) |
| $dp$ | pressure difference (kPa) |
| $F$ | economic indicator (–) |
| $P$ | pressure (kPa) |
| $\dot{Q}$ | thermal power (W) |
| $\dot{S}_{gen}$ | entropy generation rate (W/K) |
| $T$ | temperature (°C or K) |
| $\tilde{T}$ | equivalent temperature (K) |
| $UA$ | product of the overall heat transfer coefficient and heat transfer surface area (W/K) |
| $\dot{W}$ | power (W) |
| $c_p$ | heat capacity at constant pressure (kJ/kg K) |
| $h$ | enthalpy (kJ/kg) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $t_{lif}$ | lifetime in the atmosphere (yr) |
| $s$ | entropy (kJ/kg K) |
| $x$ | quality (–) |

*Subscripts*

| | |
|---|---|
| $AD$ | refrigerant side in the evaporator |
| $BC$ | refrigerant side in the condenser |
| $H$ | high temperature |
| $L$ | low temperature |
| $LMTD$ | logarithmic mean temperature difference |
| $c$ | critical |
| $comp$ | compressor |
| $cond$ | condenser |
| $evap$ | evaporator |
| exp | expansion |
| $f$ | saturated liquid |
| $g$ | saturated vapor |
| $is$ | isentropic |
| $in$ | inlet |
| $out$ | outlet |
| $recons$ | reconstruction |
| $ref$ | refrigerant |
| $sat$ | saturation |
| $sc$ | subcooling |
| $sh$ | superheating |
| $tot$ | total |

*Greek letters*

| | |
|---|---|
| $\Delta$ | difference |
| $\nu$ | specific volume (m$^3$/kg) |
| $\eta$ | efficiency |

determination of the design variables.

Having obtained the optimal evaporation and condenser temperatures by using the theoretical model, a legitimate question is how to select the most appropriate working fluid, while respecting the optimization results. The selection of the working fluid, due to the very large number of choices, is always considered as a design challenge and requires the ability to systematically screen the alternatives [16–18].

Recently, Neveu et al. [19] introduced a comprehensive approach to minimizing the investment cost in the Rankine cycle for a given output power, based on limited information, i.e. temperatures of the sources. They replaced the actual temperature by the equivalent temperature to reduce the parameters of their theoretical optimization and, thus, obtained their results in terms of equivalent temperatures, which implicitly constitute the saturation temperature, subcooling and superheating degrees. To find all thermodynamic states of the cycle as well as the mass flow rate of working fluid, they chose water as a candidate working fluid and performed their reconstruction procedure. Due to some simplifications, they assumed that the equivalent temperature and saturation temperature of the condenser are equal, which means that desuperheating and subcooling processes cannot take place in the condenser. This assumption will impose a limit for selection of the optimal working fluid. For instance, dry fluids, which have saturation vapor lines with positive slopes on their *T*-*s* diagrams, cannot be investigated by this procedure. In turn, Saloux et al. [20] overcame the aforementioned shortcoming by imposing technical constraints such as some degrees of subcooling at the inlet of the pump and then they determined the ORC thermodynamic states by using *h*-*s* diagram.

The purpose of our research is to present a novel comprehensive approach to the design of a vapor-compression refrigeration cycle that leads to the selection of the optimal working fluid based on known inlet conditions for the external heat reservoirs. The method is composed of three steps. The first step, independent of the working fluid and its thermodynamic properties, is to define the optimal equivalent temperatures of the cycle corresponding to the minimum value of the overall system conductance. To constrain the optimization problem, the second-law analysis of the cycle is developed where some thermodynamic considerations of *h*-*s* diagram integrated with equivalent temperature properties are employed to calculate the entropy generation in each device based on the operating conditions, instead of applying arbitrary dimensionless coefficients used in the literature. Moreover, the optimization problem establishes thermodynamic criteria for the pre-selection of potential refrigerants. The second step is a reconstruction procedure that systematically correlates the optimal equivalent temperatures with operating conditions, such as working pressures, temperatures, mass flow rate, subcooling and desuperheating processes, for each pre-selected refrigerants. The third step is the final selection of the most appropriate working fluid based on a capital-operating cost performance criterion. To illustrate the application of the approach presented herein, a case study is presented.

## 2. System description

The vapor-compression refrigeration cycle is used to move heat from a cold reservoir to a hot reservoir. As shown schematically in Fig. 1, it is essentially composed of two heat exchangers (a condenser and an evaporator) operating at high and low pressures, a non-isentropic compressor and an expansion valve. Heat is transferred by the working fluid from a low-temperature heat reservoir to a high-temperature heat reservoir due to the work consumed by the compressor.

The use of the first and second laws of thermodynamics between two states yields the following property relation:

$$Tds = dh - vdp \qquad (1)$$

The ratio of enthalpy to entropy variations between two states in constant-pressure process represents the equivalent temperature, also known as the exergy equivalent temperature [21].

$$\tilde{T} = \frac{\Delta h}{\Delta s} \qquad (2)$$

A valuable diagram in the analysis of a thermodynamic cycle and its components is the enthalpy-entropy, Mollier, diagram (Fig. 2a). The *h*-*s* diagram can provide intuitive insight into steady-state flow devices, as enthalpy *h* is a principal property of the first law of thermodynamics and entropy *s* is the characteristic that accounts for the second law. Equivalent temperature has an instructive geometric interpretation on