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Modeling the exergy performance of heat pump systems without using refrigerant thermodynamic properties

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ABSTRACT

This paper presents an exergy modeling approach for heat pumps which does not require the evaluation of refrigerant thermodynamic properties. Exergy balance and exergy destruction are estimated by the product of energy terms and energy quality factors. Therefore, evaluating refrigerant thermodynamic properties is not essential, only energy terms and operating temperatures (those of the refrigerant), are required. This method makes exergy analyses accessible to existing units and undefined processes. Since these temperatures are not necessarily given by the manufacturers, a mathematical method is presented for their calculations. Furthermore, to better understand the behavior of the system, a graphical exergy representation is presented; it allows the exergy destruction to be localized and the reasons of irreversibility to be identified. Based on the proposed exergy model, irreversibility is also analyzed along each energy path. It permits renewable flows from non-renewable ones to be separated and thus, the proper use of energy is emphasized. This method has been applied to existing water–water and air–air heat pump units and the results were compared with those obtained by using the classical thermodynamic cycle approach. The temperatures of the refrigerant are then given for various operating conditions and exergy assessments are discussed in detail.

1. Introduction

Renewable energy sources such as solar energy are rarely able to completely satisfy home heating requirements, therefore heat pumps are widely used for this purpose. In compression type heat pumps, heat is transferred from a heat source at low temperature to a heat sink at higher temperature by expending electrical work. Such energy flows are achieved by using an appropriate thermodynamic cycle where a refrigerant and auxiliary working fluids (air, water, brine) flow in primary and secondary loops, respectively. In general, these systems are composed of an evaporator and a condenser, where heat is transferred between the auxiliary working fluids and the refrigerant as well as a compressor and an expansion valve, where the pressure of the refrigerant increases and drops, respectively. Since these systems can run in reverse mode, they makes it possible to satisfy both heating and/or cooling requirements. In general, ambient and room air can be used as a secondary working fluid. It is obvious that in this case, the heat pump performance highly depends on the ambient air temperature, consequently the effectiveness decreases at low temperature conditions [1]. In modern efficient energy buildings, most heating loads are supplied by heat pump units while, during energy peak events, the additional energy demand is fulfilled by employing electric or gas heater supplementary systems. The relatively constant temperature of the ground at accessible depths (8 °C at 6 m depth in Canada [2]) makes the ground-source alternative very attractive [3,4]. Thus, the use of this thermal energy allows the overall electrical energy consumption to be reduced from 44% up to 72%, as compared with ambient air heat pumps and conventional equipment, respectively [5]. Solar assisted heat pumps are another technological option where the heat recovered by solar collectors is transferred to the heat pump evaporator through appropriate heat exchangers [6]; in some cases, it is also possible to achieve the evaporation of the refrigerant inside the collector itself [7,8]. From this view point, the use of several energy sources to satisfy a given building thermal load can yield better performances [1], as it has been already shown for solar assisted geothermal heat pump systems [9,10].

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Nomenclature

$\dot{D}$	exergy destruction (kW)
$\dot{Q}$	thermal power (kW)
T	temperature (°C or K)
T_{cond}	refrigerant condensation temperature (°C or K)
T_{evap}	refrigerant evaporation temperature (°C or K)
T_{23}	condenser temperature (°C or K)
T_{41}	evaporator temperature (°C or K)
$\dot{W}$	electrical power (kW)
a_{iQ}	interpolation coefficients for the evaporator thermal capacity
a_{iW}	interpolation coefficients for the compressor work
d	distance between heat pump and compressor data
h	enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
s	entropy (kJ/kg K)

Subscripts

HP	heat pump
compr	compressor
cond	condenser
evap	evaporator
id	ideal
in	inlet side of the auxiliary fluid
max	maximum
non-ren	non-renewable flow
out	outlet side of the auxiliary fluid
ren	renewable flow
valve	expansion valve
ref	refrigerant
0	reference environment state for exergy analyses

Greek letters

ΔT^{*}	temperature difference between the inlet side of the working fluid and the refrigerant in phase transition (°C or K)
$\Delta T_{cond-23}$	condenser-condensation temperature difference (°C or K)
ε	relative error (%)
ψ	exergy (kW)
θ	Carnot factor associated to the temperature T
$\tilde{\theta}$	Carnot factor associated to the exergy equivalent temperature $\tilde{T}$

However, from Carnot's postulate[1] [11], any reversible transfer or conversion of one form of energy into another have to be independent of the nature of the engine and the fluid used by the process itself. Therefore, the overall performance of any reversible system must depend only on available energy potential differences. It is obvious that for thermal units, this condition corresponds to the available temperature difference, which is responsible of driving the process. Thus, the integration of Carnot's postulate into the energy balance equation results into a definition of the exergy concept. Therefore, the exergy corresponds to the actual theoretical portion of the available energy that is able to obtain useful work along a reversible process. For this reason, the exergy concept is widely used for assessing the performance of heat pumps [1,3,4,8–10], as well as for investigating the source of losses during energy conversion processes. Applied to heat pumps, the exergy concept becomes a powerful tool that can be used not only to localize and determine mechanical component imperfections (i.e., in the evaporator, the condenser, the compressor and the expansion valve), but also to evaluate the system efficiency in a more rigorous way. However, it must be pointed out that classical exergy approaches [1,3,4,8–10] make intensive use of thermodynamic fluid properties (i.e., enthalpy and entropy) in conjunction with complete and detailed descriptions of the process thermodynamic cycles, which seems opposite to Carnot's postulate. Therefore, these particular requirements limit the exergy analysis to thermodynamic specialists and to well-defined energy systems.

To overcome this drawback, in this paper, a more natural exergy modeling approach, which is entirely based on energy terms and the corresponding operating temperatures, is proposed. In this manner, it allows the exergy assessment of existing units to be simplified, but it also permits exergy analyses to be opened up to undefined processes. In fact, the optimization of the energy equipment (i.e., components, type of fluids, etc.) from operating conditions (i.e., temperatures, energy quantities) could be easily performed using this approach. To develop this latter, heat pump energy models, necessary to perform exergy calculations, are reviewed and a mathematical method is proposed to determine the refrigerant temperatures of commercial heat pumps, which are not always provided by the manufacturers (Trane®[2], Carrier®[3], Climatemaster®[4], etc.). The benefits of such approach, which does not necessitate using explicit thermodynamic variables and allows irreversibility along energy paths to be identified, are emphasized. In addition, a graphical representation is also introduced to illustrate the heat pump exergy behavior and to better understand the reasons (energy and/or energy potential degradation) of the sources of exergy destruction. The results obtained for existing water–water and air–air Trane®[2] heat pumps, by using the proposed model are presented and compared to those given by the classical thermodynamics cycle approach.

2. The heat pump energy and exergy balance equations

In heat pumps, the refrigerant is heated at low pressure in the evaporator by cooling an auxiliary working fluid. The refrigerant pressure is then increased by a compressor and the heat is released in the condenser to a second auxiliary working fluid. In order to obtain a thermodynamic closed-cycle, an expansion valve allows the refrigerant pressure to be reduced without performing any useful work. Figs. 1 and 2 show a simplified schematic of a typical heat pump and the corresponding thermodynamic diagrams (T–s, P–h), respectively, where pressure drop along the cycle are neglected.

Based on the thermodynamic states of the cycle shown in Fig. 1, the mass and energy balances are generally written by applying the classical approach to every component, i.e., the compressor, the condenser, the expansion valve and the evaporator [1,3,4,8–10]. The evaluation of the exergy balance, with the exergy defined as $\psi = (h - h_0) - T_0\,(s - s_0)$ [12] requires, however, a previous knowledge of each thermodynamic states. Since exergy can be considered as a measure of the energy potential to perform useful work, this potential difference can be evaluated with respect to a reference state (generally the ambient air) from which no additional work

[1] *"C'est à la chaleur que doivent être attribués les grands mouvements qui frappent nos regards sur la terre . . . C'est dans cet immense réservoir que nous pouvons puiser la force mouvante nécessaire à nos besoins . . . Pour envisager dans toute sa généralité le principe de la production du mouvement par la chaleur, il faut le concevoir indépendamment d'aucun mécanisme, d'aucun agent particulier; il faut établir des raisonnements applicables, non seulement aux machines à vapeur, mais à toute machine imaginable, quelle que soit la substance mise en œuvre et quelle que soit la manière dont on agisse sur elle"*.

[2] Trademark of Ingersoll Rand.

[3] Trademark of Carrier Corporation.

[4] Trademark of ClimateMaster Inc.