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Methodology for thermal design of novel combined refrigeration/power binary fluid systems

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Abstract

Refrigeration cogeneration systems which generate power alongside with cooling improve energy utilization significantly, because such systems offer a more reasonable arrangement of energy and exergy ‘‘flows’’ within the system, which results in lower fuel consumption as compared to the separate generation of power and cooling or heating. This paper proposes several novel systems of that type, based on ammonia–water working fluid. Importantly, general principles for integration of refrigeration and power systems to produce better energy and exergy efficiencies are summarized, based primarily on the reduction of exergy destruction. The proposed plants analyzed here operate in a fully-integrated combined cycle mode with ammonia–water Rankine cycle(s) and an ammonia refrigeration cycle, interconnected by absorption, separation and heat transfer processes. It was found that the cogeneration systems have good performance, with energy and exergy efficiencies of ∼28% and 55–60%, respectively, for the base-case studied (at maximum heat input temperature of 450 °C). That efficiency is, by itself, excellent for cogeneration cycles using heat sources at these temperatures, with the exergy efficiency comparable to that of nuclear power plants. When using exhaust heat from topping gas turbine power plants, the total plant energy efficiency can rise to the remarkable value of about 57%. The hardware proposed for use is conventional and commercially available; no hardware additional to that needed in conventional power and absorption cycles is needed.

Keywords: Cogeneration; Design; Absorption system; Ammonia–water

Méthodologie pour la conception thermique de systèmes de cogénération (production de froid et d’énergie) utilisant des fluides binaires

Mots clés : Cogénération ; Conception ; Système à absorption ; Ammoniac–eau

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Nomenclature

E	exergy (kW)
h	specific enthalpy (kJ/kg)
m	mass flow rate (kg/s)
p	pressure (kPa)
p_b	turbine back-pressure (kPa)
Q	heat duty (kW)
R	refrigeration/power ratio
RR	Rectifier molar reflux ratio
SF	Split fraction
s	specific entropy (kJ/kg K)
T	temperature (K)
t	temperature (°C)
W	power output (kW)
X	ammonia mass fraction
ΔT_P	pinch point temperature difference (K)
η_1	energy efficiency (%)
η_2	exergy efficiency (%)

Subscripts

a	ambient state
EVA	evaporator
hs	heat source fluid
in	input
i	inlet
REB	reboiler
REC	rectifier
T	turbine
1, 2, …, 29	states on the cycle flow sheet

1. Introduction

Refrigeration cogeneration systems which generate power alongside with cooling improve energy utilization significantly, because such systems offer a more reasonable arrangement of energy and exergy ‘‘flows’’ within the system, which results in lower fuel consumption as compared to the separate generation of power and cooling or heating [1]. This is a practical way to improve overall system efficiency when both refrigeration and power are needed. Goswami et al. [2] proposed a combined power/refrigeration cycle using mixed working fluids and investigated its performance [3–8]. In their system, the ammonia-rich vapor from a rectifier unit, which is about 20% of the total mass flow, first expands in a turbine to generate power and then the cold turbine exhaust provides cooling by transferring only sensible heat to the chilled water. The amount of produced cooling is relatively small, and none would be produced for high turbine inlet temperature; hence the system was mainly intended to be operated with low temperature heat sources including geothermal or solar.

One of the ways that such cogeneration systems can have improved performance is by reducing the exergy loss in the heat transfer process from a variable temperature heat source, by concurrently varying the temperature of the heat sink and thus making the temperature difference between the heat source and sink more uniform along the heat exchanger (cf. [9]). This can be accomplished in a number of ways, one, most suitable when absorption refrigeration is used, is using binary-component working fluids that exhibit a variable boiling temperature during the boiling process. The ammonia–water mixture is one of the most widely used working fluids in refrigeration machines. Maloney and Robertson [10] proposed the use of an ammonia–water mixture as the working fluid in an absorption power cycle. In the combined power cycle proposed by Kalina [11], an ammonia–water mixture was employed as the working fluid in the bottoming cycle. A comparison conducted by Ibrahim and Klein [12] concluded that the Kalina cycle produces under certain conditions more power than the Maloney and Robertson cycle. These systems have power as their only usable output. Even the insertion of the absorption refrigeration unit in Wang et al.’s work [13] was not for the generation of cooling, but just to help increase the power output. Integration of the refrigeration and power components driven by the same external heat source can be accomplished by a number of configurations, several of which are proposed, analyzed and compared in this paper. An attempt is also made here to develop and demonstrate a basic general methodology for the favorable integration of such systems.

2. The main principles for system integration

The fact that refrigeration and power cycles generally operate in different temperature regions can be used in a synergistic way. For example, power cycles have some middle/low temperature heat outputs, which are impractical for generating additional power because of their low temperatures, but might be a suitable heat source for an absorption refrigeration cycle. Similarly, in the cooling cycles, some cooling capacity may exist that is not cold enough for refrigeration, but could be an appropriate heat sink to the power cycle. Their intelligent integration thus has the potential for creating a new combined cycle or cogeneration system that may have a higher efficiency.

In the cogeneration systems proposed in this paper, there are two fully-integrated sub-cycles: an absorption refrigeration cycle and a Rankine power cycle, interconnected by the absorption, separation, and heat transfer processes. They use the same working fluid, a mixture of ammonia and water, but with different concentrations, and they are supplied with heat by one external heating fluid. The energy input to the system is via several heat