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Thermodynamic relationship of subcooling power and increase of cooling output in vapour compression chiller

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ABSTRACT

The amount of improvement of the cooling output from the subcooling power has not been adequately studied by thermodynamics, and the corresponding trend has still not been realized. Therefore, this paper contributes to the understanding of the thermodynamic relationship of the subcooling power and increase of the cooling capacity. The parameter RICOSP, defined as the ratio of the rise in the cooling output to the subcooling power, is employed as the critical indicator and its expression is derived. A vapour compression chiller with subcooling is simulated to analyse RICOSP under different working conditions. It is shown that the subcooling power cannot be fully transformed into an increase of the cooling output as the speed of compressor, inlet temperature and flow rate of cooling water as well as chilled water for the chiller with the subcooling is identical to that for the system without the subcooling. Additionally, the dependence of RICOSP on the speed of the compressor, as well as on the flow rate of cooling water and chilled water, is strong. RICOSP increases by 17.4% and 8% when the speed of compressor and flow rate of cooling water are reduced by 80%, respectively. RICOSP decreases by 22.5% when the flow rate of chilled water is reduced by 80%. However, RICOSP is nearly independent of the inlet temperature of cooling water and chilled water. This paper deepens the understanding of a vapour compression chiller with subcooling.

1. Introduction

The amount of air conditioning has grown rapidly in recent years due to economic development and improved living standards. It has been shown that approximately half of building energy consumption comes from air conditioning [1]. Therefore, it is important to increase the efficiency of air conditioning for social sustainable development.

It is well known that the coefficient of performance (COP) of air conditioning has increased by approximately 6–8% as the state of refrigerant in the inlet of throttling valve is the subcooled liquid. For so-called condenser subcooling, the condenser temperature rises because of the decrease of the two-phase heat transfer area in the condenser, and there is a trade-off between the variation of the specific enthalpy in the evaporator and specific work of the compressor [2]. Moreover, the thermodynamic performance of condenser subcooling strongly depends on the type of refrigerant used [3]. In actual application, the corresponding optimal subcooling should be determined by thermoeconomics [4]. It has been recommended that an additional expansion valve should be installed between the condenser and receiver to maintain optimal subcooling during changing working condition [5].

Among the utilization of part of area in the condenser (condenser subcooling), an extra subcooler connected between the condenser and the throttling valve is commonly used to provide subcooling in the air conditioning (like Fig. 1). A cold storage unit can be utilized as a heat sink to subcool the refrigerant in the refrigeration system [6]. It has been shown that the COP of the system increases by 15% because of subcooling [7]. Among the above-mentioned cold storage units, the thermoelectric subcooler has been used in transcritical CO_2 refrigeration systems, leading to a COP increases of 25.6% under optimal conditions [8]. Furthermore, it has been shown that optimal subcooling, which maximizes the initial cost savings, is mainly influenced by the condenser temperature [9].

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Nomenclature

A	area (m^2)
COP	coefficient of performance
c_p	specific heat (kJ/kg °C)
h	specific enthalpy (kJ/kg)
K	heat transfer coefficient (W/m^2 °C)
LMTD	logarithmic mean temperature difference
m	mass flow rate (kg/s)
Q	energy (kW)
RICOSP	ratio of the increase in the cooling output to the subcooling power
T	temperature (°C)
ΔT	temperature difference (°C)
W	work of the compressor (kW)

Greek symbols

ρ	density (kg/m^3)
η	efficiency

Subscripts

e	evaporator
ef	external fluid
dis	discharge
i	inlet
if	internal fluid
nsub	no subcooling
o	outlet
s	isentropic
suc	suction

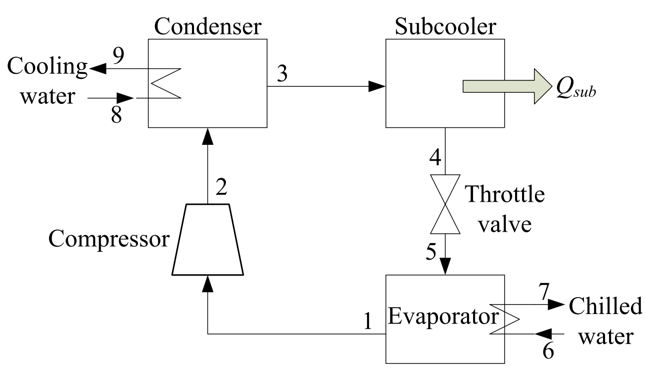

Fig. 1. Schematic of a vapour compression chiller with subcooling.

In many cases, it is difficult to obtain a heat sink that is to supply subcooling during air conditioning. Consequently, employing an extra refrigeration system as the heat sink in the subcooler has become popular in recent years. The above-mentioned solution includes two types of systems, i.e., a refrigeration system with integrated subcooling (RSIS) and refrigeration system with dedicated subcooling (RSDS) [10]. It has been shown that the optimal interstage pressure of RSIS approaches the saturated pressure associated with the arithmetic mean temperature of the condenser and evaporator [11]. Similarly, the optimal subcooler temperature is approximately halfway between the condenser temperature and evaporator temperature [12]. Moreover, special attention should be paid to the fouling of the condenser because it can increase the work of the compressor during the subcooling cycle [13]. Among vapour compression chillers, the ejector cooling system can also act as a subcooling cycle during air conditioning, and the performance of the corresponding system is good under low temperature operation conditions, i.e., when the evaporator temperature is from −40 °C to −10 °C [14]. In addition, integrated subcooling technology can significantly increase the COP of the ejector cooling system [15].

Compared with RSIS, RSDS is more convenient to use because it only includes one energy transfer and there is no mass transfer between the main cycle and subcooling cycle. The theoretical study of Llopis et al. [16] showed that the COP and cooling output of a transcritical CO_2 refrigeration system with dedicated subcooling increased by 20% and 28.8%, respectively. This improvement was verified by a subsequent experiment [17]. A similar experimental work with respect to air conditioning with dedicated subcooling was also reported, and the cooling capacity was shown to increase by 14.3% [18]. Compared with R717, R134a is more suitable as the working fluid during the main cycle [19]. Moreover, a multiple subcooler in which the heat sink was the same dedicated vapour compression chiller was presented to improve the performance of a supermarket HVAC (heating, ventilating and air conditioning) system [20]. It was shown that the performance of the above-mentioned system strongly depended on the design of the subcooler [21]. Furthermore, thermoeconomic analysis of RSDS was carried out and showed that there was a reasonable trade-off between the cost of the subcooling cycle and the subcooling of the main cycle [22].

Recently, some RSDS improvements have been led this technology to be more economical and applicable. The primary principle of these improvements is based on using free energy to drive the subcooling cycle. It has been reported that expansion work can be recovered to drive the dedicated subcooling cycle of a vapour compression chiller [23]. In addition, liquid dehumidification and evaporation equipment powered by the discharge gas of the compressor has been proposed to be used during the dedicated subcooling cycle in the refrigeration system [24]. Among the above-mentioned solutions, the $LiBr/H_2O$ absorption chiller can also be used during the dedicated subcooling cycle, and the corresponding solution is more attractive since solar energy is abundant and can be easily used. The advantage of this system is not only the increase of COP but also the adequate use of low grade solar energy [25]. Consequently, the above-mentioned solution is more economical and has great potential [26]. It was found that the size of the dedicated subcooling cycle (absorption chiller) should be designed in terms of actual solar thermal energy [27]. Furthermore, the trade-off between exergy destruction and the investment cost of the condenser, evaporator and compressor during the main cycle is important for developing a cost effective hybrid system [28].

Despite recent investigations on various types of subcooling technologies, including evaluations of the effect of subcooling, thermodynamic analysis of the whole system, experimental studies and so on, some important issues, i.e., the amount of increase of the cooling capacity that is transformed from subcooling power, have not been adequately studied by thermodynamics, and the corresponding trend has still not been determined. To the best of our knowledge, although growth of the cooling output by subcooling power has been observed in experiments and the corresponding difference has been mentioned [17,18], the quantitative trend and mechanism of difference in both parameters have not been