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Approaching the performance limit for economized cycles using simplified cycles

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ABSTRACT

Modifications such as economization aim to improve the efficiency of vapor compression equipment by cooling the refrigerant during the compression process. A previous study (Mathison et al., 2010) explored the theoretical limit to cycle performance with economizing, which was defined as the performance when a saturated vapor state was maintained in the compressor by continuously injecting a two-phase mixture. However, achieving continuous injection and controlling the quality of the injected refrigerant poses a substantial challenge. Therefore, the current paper investigates the ability of an economized cycle with saturated vapor injection through a finite number of ports to approach the limiting cycle performance. For an air-conditioner using R-410A with an evaporation temperature of 5 °C and a condensing temperature of 40 °C, the model predicts that injecting saturated vapor through three ports will improve the COP by 12%, which is approximately 67% of the maximum benefit provided by economizing in the limiting case.

Approche de la performance limite pour des cycles à économiseur utilisant des cycles simplifiés

Mots clés : Système multiétagé ; Modélisation ; Injection ; Economies d'énergie ; Cycle thermodynamique

1. Introduction

1.1. Background

The ability of cycle modifications such as intercooling and economizing to improve the performance of vapor compression equipment by reducing the compressor power consumption and, in some cases, improving the cooling capacity has been demonstrated both experimentally and theoretically (Bertsch and Groll, 2008; Cho et al., 2009; Torella et al., 2009; Wang et al., 2009; Winandy and Lebrun, 2002). Even small improvements in energy efficiency provided by these modifications translate to significant overall energy savings due to the widespread use of vapor compression equipment. Therefore, these technologies prove increasingly important as

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Nomenclature

COP_{econ}	Coefficient of performance of the economized cycle [–]
COP_{norm}	Normalized coefficient of performance [–]
COP_{ss}	Coefficient of performance of the single-stage cycle without economization [–]
h	Specific enthalpy [kJ kg^{-1}]
$\dot{m}_{comp}$	Mass flow rate through the compressor [kg s^{-1}]
$\dot{m}_{cond}$	Mass flow rate through the condenser [kg s^{-1}]
$\dot{m}_{inj}$	Mass flow rate through the injection line [kg s^{-1}]
N	Number of injection ports [–]
p	Pressure [kPa]
r_{comp}	Ratio of mass flow rate in the compressor to mass flow rate in the condenser [–]
r_{inj}	Ratio of mass flow rate in the injection line to mass flow rate in the condenser [–]
x	Quality [–]

concern over energy costs, energy security, and environmental sustainability continue to grow.

Intercoolers and economizers are typically installed between compressor stages, but the cost of multi-stage compressors often prevents their implementation in smaller scale applications. The development of compressors with ports for refrigerant injection during the compression process presents a more cost-effective method for incorporating economization into vapor compression cycles, improving the viability of economizing for all applications. A scroll compressor with a single refrigerant injection port has been patented by Copeland Corporation (Perevozchikov, 2003) and marketed for air-conditioning applications, but other rotary compressor designs such as the rolling piston or screw could also be modified to incorporate injection ports. In addition, the number of injection ports can be increased at relatively low cost to essentially break the compression process into multiple stages within a single compression chamber. As the number of injection ports increases, providing more opportunities to inject cool, economized refrigerant, the performance of the compressor and the overall system should increase. This hypothesis is supported by the results of an experimentally validated model developed by Jung et al. (1999), which indicate that a cycle with three-stage compression and two economizers has a higher coefficient of performance (COP) than a cycle with two-stage compression and one economizer.

Therefore, Mathison et al. (2010) developed a thermodynamic model of the vapor compression cycle to study the effect of increasing the number of injection ports in an economized cycle and to predict the theoretical limit to cycle performance when refrigerant is injected continuously. The model assumes that the compressor operates with a constant isentropic efficiency that is unaffected by changing the number of injection ports. In addition, it is assumed that the injection process occurs instantaneously, at a constant pressure, and the injected refrigerant mixes instantaneously with the refrigerant in the compression chamber. The benefits of economizing will be maximized when the economized refrigerant provides as much cooling as possible; however, in most compressors the refrigerant in the compression chamber should remain in the vapor phase to avoid damage due to liquid droplets. While scroll compressors can tolerate the presence of liquid, supplying a two-phase refrigerant to the condenser will tend to decrease its effectiveness because the convective heat transfer coefficient decreases with quality. For these reasons, it is assumed that the limiting performance with economization is achieved when the refrigerant in the working chamber remains at the saturated vapor state throughout the compression process.

In order to maintain a saturated vapor state in the compression chamber, it is necessary to inject a two-phase refrigerant mixture. Although this will introduce liquid into the compressor, it is assumed that the injected liquid is instantaneously vaporized as it absorbs the heat of compression and thus, will not cause any damage. The quality of the injected refrigerant is determined such that the instantaneous injection and mixing process results in a saturated vapor state in the compression chamber. The economized refrigerant is supplied to the injection ports by phase separators, as Fig. 1 illustrates for the case with three injection ports operating at three intermediate pressures. It is assumed that the phase separators operate by drawing off the saturated vapor generated during the expansion process, plus enough liquid to achieve the desired quality in the injection line. The result is that the refrigerant entering each expansion valve is a saturated liquid. Fig. 2 plots the state of the refrigerant at each point in the cycle on a pressure-enthalpy diagram with labels corresponding to the cycle in Fig. 1. The results are presented for a cycle using R-410A with an evaporating temperature of −20 °C, a condensing temperature of 50 °C, and a compressor efficiency of 70%; the superheat at the evaporator exit and the subcooling at the condenser exit are both specified as 0 °C.

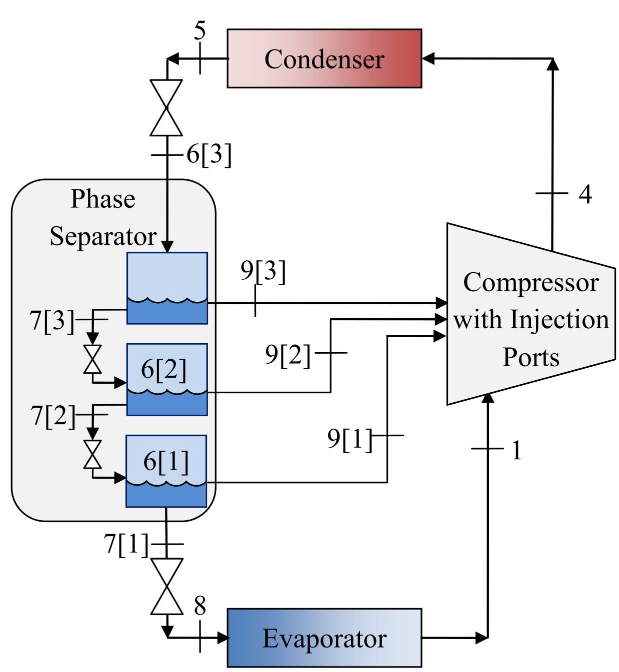

Fig. 1 – Vapor compression cycle with injection and flash-tank economization.