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Effect of the condenser subcooling on the performance of vapor compression systems

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ABSTRACT

This paper presents a theoretical study about the effect of condenser subcooling on the performance of vapor-compression systems. It is shown that, as condenser subcooling increases, the COP reaches a maximum as a result of a trade-off between increasing refrigerating effect and specific compression work. The thermodynamic properties associated with the relative increase in refrigerating effect, i.e. liquid specific heat and latent heat of vaporization, are dominant to determine the maximum COP improvement with condenser subcooling. Refrigerants with large latent heat of vaporization tend to benefit less from condenser subcooling. For an air conditioning system, results indicate that the R1234yf (+8.4%) would benefit the most from condenser subcooling in comparison to R410A (7.0%), R134a (5.9%) and R717 (2.7%) due to its smaller latent heat of vaporization. On the other hand, the value of COP maximizing subcooling does not seem to be a strong function of thermodynamic properties.

Effet du sous-refroidissement du condenseur sur la performance de systèmes à compression de vapeur

Mots clés : Condenseur ; Sous-refroidissement ; Coefficient de performance (COP) ; Frigorigènes de remplacement ; Charge en frigorigène

1. Introduction

The state of the refrigerant entering the expansion device of conventional vapor compression cycles is usually assumed to be saturated liquid. However, liquid cooling below saturation can increase the refrigerating effect and potentially improve the coefficient of performance (COP). From the perspective of the second law of thermodynamics, liquid subcooling reduces throttling losses resulting from an isenthalpic expansion.

Subcooling liquid before the expansion process can be obtained through different approaches. For instance, the conventional cycle can be modified by adding extra components to subcool liquid between exit of the condenser and inlet of the expansion device. Typical examples are internal heat exchangers in single-stage cycles (Domanski and Didion,

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Nomenclature

COP	coefficient of performance (–)
q	enthalpy difference across the evaporator (kJ kg^{-1})
SH	superheated vapor region (–)
SC	subcooled liquid region (–)
T	temperature (°C)
TP	two-phase region (–)
w	specific compression work (kJ kg^{-1} K^{-1})
Subscripts	
avg	average
c	condenser
e	evaporator
fg	liquid–vapor
in	inlet
p	constant pressure
out	outlet
sat	saturation
sub	subcooling
Greek	
Δ	difference

1994) and in two-stage cycles. Subcooling can also be achieved by an auxiliary cooling system such as a thermoelectric device (Radermacher et al., 2007), a secondary vapor compression system – also known as mechanical subcooling (Couvillion et al., 1988), just to mention a few examples. Other available coolant supplies, such as condensate water from evaporator (Peterson, 1997), could also be used to subcool liquid exiting the condenser.

A common way to obtain subcooling is by using an additional heat-sink cooled heat exchanger, usually denominated subcooler. Typically, a high-side pressure receiver is installed between the condenser and the subcooler in order to separate liquid from vapor before liquid runs through the subcooler. In shell-and-tube condensers, a receiver may not be necessary since the shell acts as a liquid–vapor separator. One can think of the subcooler not only as separate heat exchanger but as part of a then larger condenser which has some of its surface allocated to subcool liquid. In fact, the most conventional way to obtain subcooling in systems without a liquid receiver is by utilizing part of condenser heat transfer area to cool down the liquid below the saturation temperature. Rather than in a high-side pressure receiver, the liquid–vapor interface is eliminated inside the condenser tubes, such as those of air-cooled tube-in-fin and water-cooled tube-in-tube heat exchangers, as liquid refrigerant accumulates towards the exit of the heat exchanger. The so-called condenser subcooling is typically obtained during a refrigerant charging procedure. The question raised by Gosney (1982) is whether one would be better off using the subcooling heat transfer surface, either within the condenser or in a separate subcooler, to reduce the condensing pressure and consequently the compression work.

According to Gosney (1982), the relative gain in specific refrigerating effect through liquid subcooling depends on the ratio of liquid specific heat to the refrigerant enthalpy difference across the evaporator. Linton et al. (1992) experimentally investigated the effect of condenser liquid subcooling on a refrigeration system performance. Results showed that the cooling COP and refrigeration capacity of all three refrigerants benefited from subcooling increase (from 6 °C to 18 °C): R134a (12.5%), R12 (10.5%) and R152a (10%), while condensing temperature was kept constant. These values followed closely the theoretical increase in refrigerating effect calculated using the approach described by Gosney (1982) since condensing temperature was kept artificially constant. Selbas et al. (2006) performed a thermoeconomic optimization of desuperheating, condensing, subcooling, evaporating and superheating heat transfer areas using a combination of exergy and economic concepts. The authors claimed that a subcooling of around 5 °C would maximize the COP.

Subcooling has also been subject of publications related to automotive air conditioners. These systems are usually equipped with either a high-side liquid receiver or a low-side accumulator in order to absorb fluctuations in refrigerant charge due to change in operating conditions and to maintain a constant performance against small refrigerant leakages. Yamanaka et al. (1997) presented a concept of a subcooler system in which the liquid receiver is installed before the last pass of a parallel flow microchannel condenser rather than at the exit of the condenser. COP would benefit from subcooling due to an increase in enthalpy difference across evaporator. Condensers with integrated receiver and subcooler pass have become standard in state-of-the-art automotive air conditioning systems. Pomme (1999) presented a similar study, in which subcooling was generated by a pre-expansion valve between the condenser exit and a liquid receiver.

A few publications that examined the influence of the refrigerant charge on the COP indirectly explored the relationship between subcooling and COP. Corberan et al. (2008) maximized COP by varying the refrigerant charge in an R290 heat pump equipped with a thermostatic expansion valve. They explained that the system responded to increasing charge by rising in condenser subcooling since no receiver was installed. The COP maximizing charge was related to a COP maximizing subcooling. Primal and Lundqvist (2005) had also optimized the charge of an R290 domestic water heat pump and found the corresponding subcooling to be 4–5 °C. Poggi et al. (2008) published a review about refrigerant charge issues in refrigeration systems. They also related COP maximizing refrigerant charges to an appropriate subcooling in the condenser.

Although condenser subcooling is a practical issue in refrigeration and air conditioning systems, the authors found that studies specifically about condenser subcooling are very limited in the open literature. This study is an attempt to start filling up this gap. Previous studies on subcooling, such as Allerton et al. (1948), Couvillion et al. (1988), Linton et al. (1992) and Şencan et al. (2006), have not explored the potential performance trade-off associated with the subcooling obtained within the condenser. Therefore, the first part of this article will theoretically explore this trade-off with cycle analysis. Then, important thermodynamic properties related to this trade-off will be identified and a sensitivity analysis will be presented for different refrigerants. Second, a comprehensive simulation model of an air conditioner will be used estimate