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Refrigerant charge reduction in low-temperature transport refrigerator with the eutectic plate evaporator

L. Vaitkus*, V. Dagilis

Kaunas University of Technology, K. Donelaicio g. 73, Kaunas LT-44029, Lithuania

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ABSTRACT

In the article a problem of refrigerant charge reduction of the transport refrigerating system with eutectic plate evaporator is analysed. Such system generates cold during the night, with the vehicle in the depot, and during the day it operates without access to electricity supply. Due to weight limitations the system is equipped with single-stage compressor, which is normally operated at very low evaporation temperatures (−43 ÷ −45 °C during the crystallization of eutectic mixture) and high compression ratios. At the initial stage of pull-down the temperature of eutectic plates is high and therefore maximum operation pressure (MOP) control is required. Other important features with regard to charge minimization are big thermal inertia and relatively big inner volume of the evaporator.

During the research it was found that the refrigerant charge is strongly influenced by a system used for MOP control. The other charge influencing factors were also analysed. Two low charge refrigerators with different evaporator setup and MOP control systems were developed and tested. The refrigerant charge was reduced from 4.1 kg to 2.4 and 2.5 kg of R507 without a negative impact on performance. The possibility of further charge reduction is also discussed. The problem is analysed on the example of eutectic system, but the conclusions apply also to all low-temperature single stage systems with some means of MOP control.

Réduction de la charge en frigorigène dans un réfrigérateur pour le transport à basse température grâce à l'évaporateur à plaques eutectiques

Mots clés : Réfrigérateur ; Réduction de la charge en frigorigène ; Régulation de la performance de fonctionnement maximale ; Plaques eutectiques

* *Corresponding author*. Tel.: +370 610 27 664.
E-mail addresses: liutauras.vaitkus@ktu.lt (L. Vaitkus), vytautas.dagilis@ktu.lt (V. Dagilis).
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1. Review of charge reduction strategies

Considering the environmental challenges, the refrigerant charge minimization is one of the most important targets for refrigeration and air conditioning applications. The low charge systems ensure the double positive effect: the reduction of annual emissions from systems, and the prevention of greenhouse gas (GHG) stock build up, reducing 'End of Life' emission in the future. Any measure reducing refrigerant emissions must be estimated considering GHG emissions related to energy use. According to Harmelink et al. (2002) any system adaptation should only be carried out if it results in lower Total Equivalent Warming Impact (TEWI).

The review was focused on existing charge reduction strategies and recommendations for preferable system setup.

Cavallini et al. (2010), Hrnjak and Litch (2008), and Primal et al. (2001, 2004) investigated the performance of a heat pump and refrigerating systems with plate and microchannel heat exchangers. It was found that the use of microchannel heat exchangers considerably reduces refrigerant charge. The COP and capacity were more or less constant when the charge was above a certain minimum level, below which the COP and capacity dropped significantly due to 'starvation' of the evaporator.

Corberán et al. (2008) investigated the charge distribution inside the refrigerating system. It was found that most of the charge (about 50%) is in the condenser. The total mass in all components of the system, with the exception of the condenser, was non-dependent on the charge variation - the condenser stores the extra charge in the system varying the subcooling. The subcooling in the condenser is closely related to refrigerant charge and to system performance.

It is generally taken for granted that there should be no subcooling for optimal operation. According to Stoecker (2004), subcooling is not normally desired. The same assumption is used by Vjacheslav et al. (2001). However, in (Primal et al., 2004; Corberán et al., 2008; Tassou and Grace, 2005; Choi and Kim, 2002, 2004; Cho et al., 2005) we see different results. Tassou and Grace (2005) have found that for water-to-water chiller with R404A refrigerant the optimal subcooling was more than 5 K. Choi and Kim (Choi and Kim, 2002, 2004) also found optimal subcooling of 4–5 K for heat pump with R22, and 2–3.5 K for system with R407C. Primal et al. (Primal et al., 2004) found that the optimum subcooling for R290 heat pump was 4–5 K.

The optimality of subcooling was analysed by Jensen and Skogestad (2007a). For ammonia refrigerating system they found that subcooling by 4.66 K reduces the compression work by 1.74%, compared to the case without subcooling. The optimal degree of subcooling becomes smaller as the heat transfer (UA-value) is increased; with an infinite heat transfer area the subcooling is not optimal. Since optimality of the charge is mainly related to the subcooling, the possible gains from the charge optimization are not significant – about 2%. In addition, the systems with optimized charge are not sensitive to the charge variation. Grace et al. (2005) and Tassou and Grace (2005) found that the COP of vapour compression refrigeration system was relatively constant at its maximum across a broad range of charge levels, 25% below to 25% above the design value.

Choi and Kim (2002, 2004) investigated water-to-water heat pumps with electronic expansion valves (EEV) and capillary tube. The results indicate that the EEV system was less sensitive to refrigerant charge variation. Similar results were obtained by Goswami et al. (1997) and Farzad (1990). Björk and Palm (2006) found a low sensitivity of household refrigerator to charge. According to Cho et al. (2005) the transcritical CO_2 heat pump showed higher performance sensitivity to refrigerant charge comparing to that of R22, R407C and R410A systems.

In the works (Tassou and Grace, 2005; Choi and Kim, 2002, 2004; Grace et al., 2005; Goswami et al., 1997; Farzad, 1990) independently of the system, refrigerant, etc. the similar pattern is clear: too little charge does cause incomplete condensation, two-phase feeding of the expansion valve and inadequate filling of the evaporator. As long as the charge is sufficient to ensure the complete condensation, the effect of further charge increase depends on used system. Most of the discussed works investigated the systems without a high pressure receiver. In such system liquid subcooling in the condenser is possible, performance depends on the charge and optimal charge does exist. The expected COP increase achieved through liquid subcooling comparing to saturated outlet is about 2% plus some positive effect from lower pressure drop in the piping and equipment. This COP increase is not free – the liquid subcooling is a large contributor to total charge since the subcooling region holds a significant fraction of the total charge inventory. Thus, if the low charge system is on target, it is advantageous to reduce subcooling. Actually, for the low charge system one should not optimize the charge for maximum COP, but rather just ensure complete condensation.

Considering vapour superheat in the evaporator, the relationship to refrigerant charge is weak. In the most of the previously discussed systems the superheat was determined by the control system rather than by the charge.

Considering the expansion device, both the systems with TXV and EEV are less sensitive to charge, when compared to a system with capillary tube. According to reported results, there are no significant differences in the charges of TXV and EEV controlled systems.

The big attention should be paid to the condenser, and microchannel or mini-channel condensers are often recommended for the low-charge system. Palm (Palm, 2007) investigated refrigerating system with a minimum charge of refrigerant. In addition to mini-channel heat exchangers, his suggestions for charge reduction are (1) use of indirect system, (2) use of low-pressure receiver on the suction line rather than the common high-pressure receiver on the liquid line, (3) use a capillary tube as expansion device, (4) use compressor with small internal volume and small oil charge, (5) use non-miscible oils.

Vrinat et al. (2000) reported that the liquid filling rate of flooded evaporators would be a little higher than that of direct expansion fed evaporators with a respectively, 25% and a 10% volume filling. A strict concern of charge reduction will result in preferring the evaporator's direct expansion supplying. Poggi et al. (2008) also presented a review of the refrigerant charge studies. Macchi et al. (1999) reported that in the studied cases the ratio between the charge in the liquid pipes and the