Title: Study of scroll compressors with vapor-injection for heat pumps operating in cold climates or in high-temperature water heating applications

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Abstract

Nowadays, one of the most important challenges in the residential and industrial sectors is the efficiency improvement of the equipment and systems used for heating and hot water production. The main objective is to reduce the consumption of fossil fuels and CO_2 emissions in these applications. In this context, heat pumps are considered to be an effective technology as an alternative to boilers for the production of hot water and heating. However, when the air-to-water heat pumps work in extreme conditions, that is, at low evaporating temperatures or at high condensing temperatures, the performance (COP) and the capacity of the heat pumps are reduced due mainly to the limitations in the compression process. Under these conditions, the compressor's isentropic and volumetric efficiencies significantly decrease, while the discharge temperature increases. One of the main solutions to improve the capacity and COP of heat pumps is the two-stage compression cycles with vapor-injection. In such systems, vapor-injection compressors and two-stage compressors can be used. The most commonly used compressor technologies are the scroll and the reciprocating compressors.

This Ph.D. thesis presents a study of scroll compressors with vapor-injection (SCVI) for heat pumps operating in cold climates or in high-temperature water heating applications. To do so, firstly, an SCVI was experimentally compared with a two-stage reciprocating compressor (TSRC) working with R-407C under extreme conditions. The comparison was made in terms of compressor efficiencies, capacity, COP, and seasonal COP, both for heating and cooling modes. The results give a general idea about the application range of the studied compressors and the differences in the compressors' performance. Nevertheless, several restrictions in the compressors' characterization and the cycle analysis were identified. This motivated us to deepen in the study of the two-stage compression cycle and its components. The next step was performing a theoretical analysis of two-stage compression cycles for heating applications, where the intermediate pressure and the injection ratio were identified as the most influential system parameters on the COP. The intermediate pressure was optimized for two vapor-injection configurations (flash tank and economizer) using several refrigerants. Based on the optimization results, a correlation was proposed that allows obtaining the optimal intermediate pressure of the cycle, considering the influence of the subcooling at the condenser outlet. In addition, a theoretical analysis of the influence of the design of the system components on the COP of the cycle was performed.

Once the thermodynamic analysis of the two-stage cycle was carried out, the study was deepened at the component level. The most critical factor in the system is the compressor performance. Hence, the next step was evaluating the influence of several compression systems with vapor-injection on the COP. Three compressor technologies were taken into account, an SCVI, a TSRC and a two-stage scroll compressor (TSSC). These compressor technologies were characterized and modeled in order to study their performance. To do so, a new methodology to characterize SCVI was proposed. This methodology allows evaluating the compressor performance independently of the injection mechanism used in the cycle. A linear correlation was identified between the refrigerant injection ratio and the intermediate compression ratio. This correlation is used to determine the injection mass flow as a function of the intermediate pressure.

Then, a semi-empirical model of scroll compressors and a methodology to extend the model for scroll compressors with vapor-injection was proposed. The models were adjusted and validated using experimental data from four scroll compressors working with R-290 and an SCVI compressor working with R-407C. Finally, an SCVI was compared with two two-stage compressors, a TSSC, and a TSRC, working in extreme conditions. The displacement ratio of the two-stage compressors was optimized. Results show that, at the nominal operating conditions (T_e=-15 °C, T_c=50 °C), the optimal displacement ratio of the TSSC is 0.58, and of the TSRC is 0.57. The TSSC achieves 6% larger COP than the SCVI and 11.7% larger COP than the TSRC. Under a wide range of operating conditions, the SCVI presents a better efficiency and COP for pressure ratios below 5. For higher-pressure ratios, the TSSC presents better performance and achieves lower discharge temperature. It is concluded that the SCVI is an easy solution to implement from the point of view of machining, which allows extending the working map of the single-stage compressors. However, the results show that the two-stage compression technology gets further improve the COP of the cycle and the capacity, with a greater reduction of the discharge temperature operating under extreme conditions.