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Performance analysis of a centrifugal compressor in a vapor compression refrigeration cycle with an energy-based approach

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Abstract

This study investigates the performance of a centrifugal compressor in a vapor compression refrigeration cycle using an energy-based approach. The effects of parameters such as mass flow rate, pressure ratio, and compressor operating conditions were analyzed. Numerical analyses and thermodynamic modeling demonstrated that optimizing intermediate pressures and selecting suitable refrigerants can significantly enhance system efficiency. Results revealed that in two-stage configurations, COP increased by approximately 8% for R134a and 23% for R744 compared to single-stage configurations. The maximum efficiency was achieved when the intermediate pressure was 1.7 times the evaporator pressure.

Keywords: Centrifugal Vapor Compression Chiller; Two-Stage Compressor; Vapor Compression Refrigeration Cycle; Surge

1. Introduction

The increasing demand for refrigeration and air conditioning systems across various industries and domestic applications has highlighted the importance of improving energy efficiency and reducing operational costs. One of the key challenges in this field is minimizing energy losses and optimizing the performance of essential components, such as centrifugal compressors. These compressors are widely used in industrial refrigeration systems due to their high capacity, efficiency, and ability to operate under high pressure conditions.

Previous research has demonstrated that the performance of centrifugal compressors is highly influenced by operating conditions such as mass flow rate, pressure ratio, and temperature and pressure distribution within the compressor chamber. For instance, studies conducted by Zhang et al [1]. Showed that adjusting the intermediate pressure in two-stage cycles significantly improves system efficiency and prevents unstable conditions like surge. Royita and Sarsti [2] optimized the refrigeration process with a two-stage centrifugal compressor and flash intercooler. Their goal was to achieve the maximum coefficient of performance (COP) by modeling thermodynamic properties and mass transfer.

Furthermore, research by Goktun [3]. investigated the impact of refrigerant type on the performance of vapor compression cycles, revealing that selecting refrigerants with optimal thermodynamic properties not only enhances system efficiency but also reduces environmental impact. For example, R134a has shown superior performance compared to many other refrigerants due to its favorable physical and chemical properties.

Despite these advancements, numerous challenges remain in optimizing the performance of centrifugal compressors. These include identifying the optimal intermediate pressure, examining critical mass flow rate conditions, and analyzing internal flow dynamics. This study aims to address these challenges by employing thermodynamic modeling and numerical analysis to provide novel insights into enhancing the efficiency and stability of vapor compression systems.

2. Methodology and Modeling:

Thermodynamic modeling of the system was conducted using EES software, while CFX was employed for numerical flow analysis. The study examined single-stage and two-stage configurations using R134a and R744 as primary refrigerants. Parameters such as mass flow rate, pressure ratio, and intermediate pressure were evaluated. Data validation through numerical simulations provided insights into optimal compressor operating conditions.

Numerical analysis is conducted using Ansys and its modules like Vista CCD, TurboGrid, BladeGen, and CFX. Boundary conditions are set in Vista CCD to generate compressor performance maps. The impeller design is transferred to BladeGen for geometry creation, meshed in TurboGrid, and evaluated in CFX, with results displayed in CFD Post.

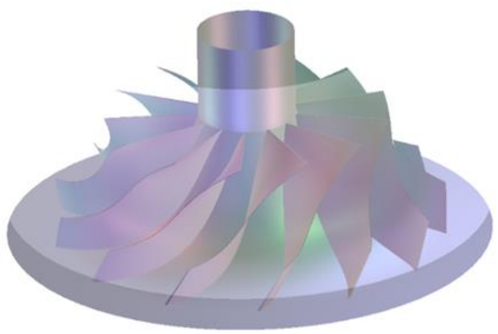

Figure 1. The geometric model created in BladeGen software.

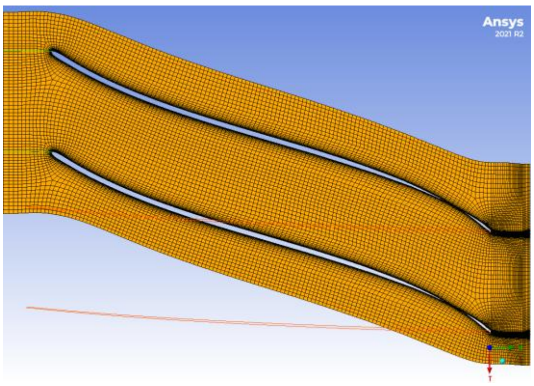

Figure 2. The meshed impeller in the TurboGrid , showing a detailed view of two impeller blades.

Table 1. Input parameters to the CFX software.

Analysis type	Steady state
Reference pressure	0 atm
Heat transfer model	Total Energy
Turbolance model	Shear stress transport
Inlet boundary condition	Mass flow inlet
outlet boundary condition	P-static outlet
Residual target	0.00001
Interface	periodic

3. Results and Analysis:

a. Cycle Performance with Different Refrigerants:

- R134a demonstrated superior thermodynamic properties, leading to higher system efficiency compared to R744.
- In two-stage configurations, COP increased by approximately 8% for R134a and 23% for R744.

Table 2. Performance of single-stage and two-stage chillers with different refrigerants.

Refrigerant	COP_R Two stage	COP_R Single stage
R134a	7.754	7.18
R744	5.58	4.248
R717	6.916	6.63
R410a	6.481	5.87
R404a	6.352	5.59
R32	6.583	6.11
R290	6.786	6.19
R600a	6.993	6.43
R1234yf	6.721	6.01

b. Intermediate Pressure Optimization:

- The optimal intermediate pressure for maximum system efficiency was approximately 1.7 times the evaporator pressure.
- Proper intermediate pressure design significantly reduced energy losses and improved system stability.
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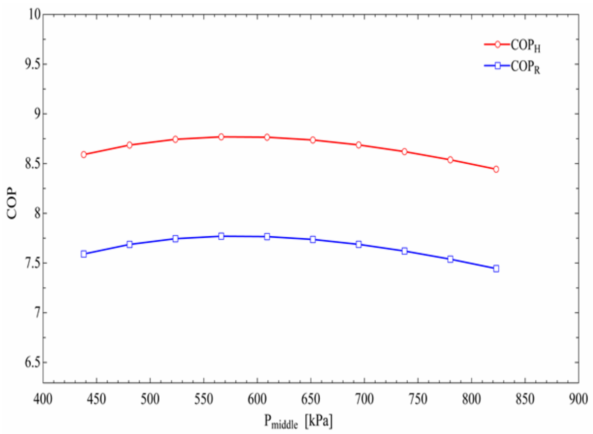

Figure 3. The Effect of Intermediate Pressure on the Performance Coefficient of a Two-Stage Cycle.

c. Numerical Analysis of the Compressor:

- High and low mass flow rates pushed the compressor towards unstable conditions (surge and choke).

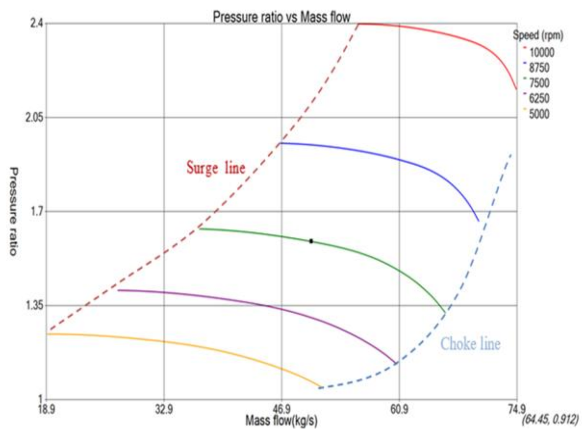

Figure 4. Performance Map of the Second Compressor Impeller: Pressure Ratio vs. Flow Rate at Different Speeds.

- Mach number analysis showed that pressure and velocity distribution had a direct impact on compressor performance.
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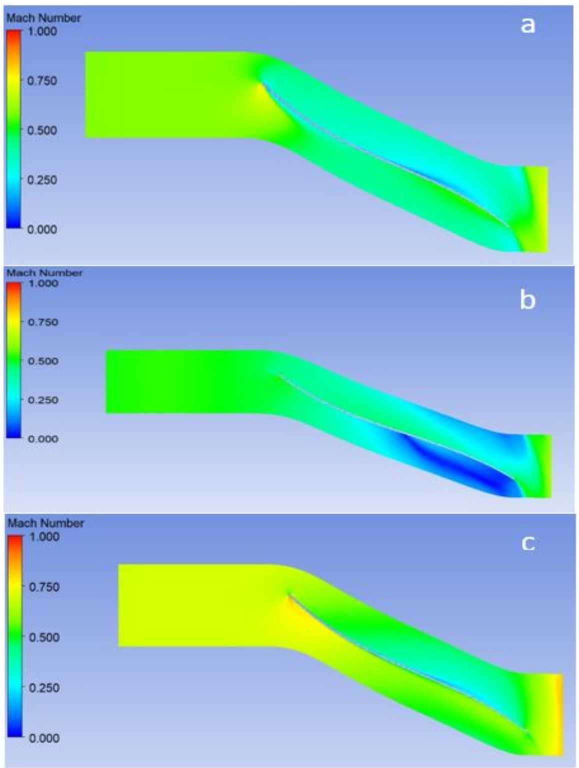

Figure 4. Blade-to-Blade View of Mach Number Distribution in the First Impeller at Flow Rates of 40 kg/s (a), 20 kg/s (b), and 60 kg/s (c).

4. Discussion and Conclusion:

This research examines the performance of centrifugal compression chillers operating in both single and two-stage refrigeration cycles. The thermodynamic modeling was conducted under ideal conditions, followed by a detailed analysis of a real chiller system under varying operational capacities. The study evaluated the effects of changes in system capacity and intermediate pressure on the compressor's performance and the system's coefficient of performance COP_R.

Results demonstrated that increasing the intermediate pressure from near the evaporator pressure (450 kPa) to a value near the condenser pressure (700 kPa) initially improved COP_R but subsequently caused a decline, with the optimal point observed at 576.7 kPa. In single-stage and two-stage cycles, COP_R decreased from 11.83 and 12.35 to approximately 3.38 and 3.93, respectively. Furthermore, COP_R was found to be highly sensitive to the isentropic efficiency of the compressor. A reduction in this efficiency from 1 to 0.6 caused a drop in COP_R from 7.77 to 4.2. For identical conditions, the two-stage cycle exhibited an 8% higher efficiency for refrigerant R134a and a 23% increase for R744 compared to the single-stage cycle.

Analysis of the compressor's performance showed that isentropic efficiency decreased as the refrigerant mass flow rate increased; a 50% rise in flow rate led to a 5% drop in efficiency. Such changes are critical for centrifugal compressors, as they can push the compressor out of its optimal operating range, leading to issues like surge and choke phenomena.

Lastly, changes in refrigerant mass flow rates were analyzed to assess their impact on the Mach number distribution across different regions of the impeller and to evaluate their effect on the system's overall performance.

5. References

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