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DYNAMIC SIMULATION AND PERFORMANCE COMPARISON OF TWO-STAGE AND SINGLE-STAGE HEAT PUMPS WITH INTERMEDIATE TEMPERATURE CONTROL

Zahra Hajabdollahi[1*], Zhibin Yu[1]

[1] Department of Mechanical and Aerospace Engineering, University of Liverpool, Liverpool, L3 5TR, United Kingdom

1. ABSTRACT

This paper presents the dynamic simulation of an air-to-air heat pump using OpenModelica, with R1234yf as the refrigerant. The study evaluates the performance of a two-stage heat pump and compares it with a single-stage heat pump by analyzing the coefficient of performance (COP) in both configurations. In both the single-stage and two-stage heat pumps, the condenser temperature is controlled to maintain a temperature of 65°C. Additionally, the intermediate temperature in the two-stage system is actively controlled to enhance the COP. The results highlight the differences in efficiency and performance between the two systems, providing insights into the advantages of using a two-stage configuration with R1234yf.

2. INTRODUCTION

The necessity of dynamic simulation in the study of heat pump systems cannot be overstated. It plays a crucial role in accurately predicting system performance and efficiency under varying operating conditions, which is vital for optimizing design, improving control strategies, and ensuring reliability and energy savings in real-world applications [1-4]. Given this critical role, numerous studies have focused on dynamic simulation to enhance our understanding and optimization of heat pump systems. Niemelä et al. [5] simulates and validates heat pump systems within building energy simulations using IDA ICE software and field tests, demonstrating accurate energy performance simulation for various heat pump types under different installation methods. In another research Yang et al. [6] presented an updated method for dynamically simulating ground-coupled heat pump (GCHP) systems using an analytical heat transfer model for borehole heat exchangers (BHE), validated experimentally and theoretically, achieving a predicted relative error of less than 3%. Despite the advancements in dynamic simulation of heat pump systems, there is a noticeable gap in the literature regarding the dynamic simulation of two-stage heat pumps. To address this, our study focuses on developing a dynamic simulation model for a two-stage air-to-air heat pump using R1234yf as the refrigerant. We aim to compare the performance and efficiency of this two-stage system with a traditional single-stage heat pump under dynamic operating conditions. By controlling the condenser temperature in both configurations to maintain a constant 65°C, we will evaluate the coefficient of performance (COP) and other key performance metrics, providing valuable insights into the benefits and potential improvements offered by the two-stage configuration.

3. METHDOLOGY

This model is designed for incompressible fluid applications and features selectable valve characteristics, including linear, parabolic, and equal-percentage curves. The valve's flow coefficient can be specified using various standards. The reference mass flow rate is calculated based on the chosen flow coefficient and the fluid density. The valve characteristics are determined by a function, which adjusts the valve opening based on the control signal and minimum valve position. The Fig.1 represents a schematic diagram of a two-stage heat pump system, designed to enhance efficiency and performance through staged compression and heat exchange processes. The refrigerant

*Corresponding Author: zahra.hajabdollahi-ouderji@liverpool.ac.uk

flows through various components, undergoing compression, heat exchange, and expansion. The system includes a two-stage compression process where the refrigerant is compressed initially, passes through an intermediate heat exchanger, and then undergoes further compression. A crucial aspect of this system is the inclusion of controllers to manage the intermediate temperature in the intermediate tank and the temperature at the condenser. These controllers are essential for maintaining optimal operational conditions and ensuring the system's efficiency and stability.

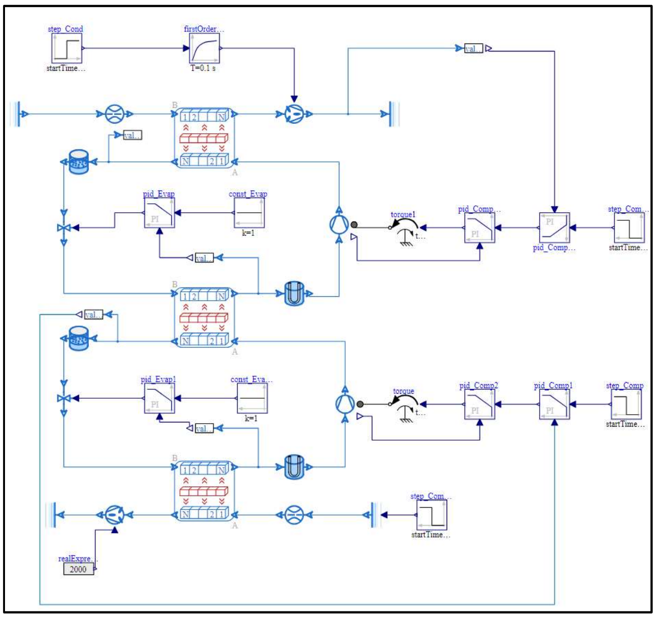

Fig. 1. Schematic diagram of a two-stage heat pump system with integrated controllers for regulating intermediate tank temperature and condenser temperature in Modelica.

4. RESULTS

Fig. 2. a displays the temperature response of both the evaporator and condenser in the two-stage heat pump system over time.

(a) **(b)**

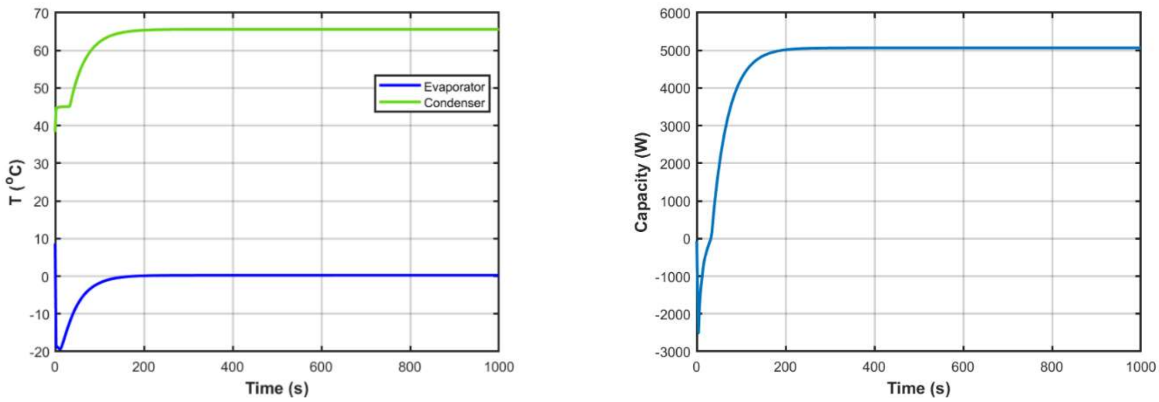

Fig. 2. (a), Temperature response of the evaporator and condenser in the two-stage heat pump system over time, (b). Condenser heat rejection.

The green line represents the condenser temperature, which starts at around 40°C and rapidly increases to approximately 65°C within the first 200 seconds, after which it stabilizes. This behavior indicates the effective performance of the condenser, quickly reaching and maintaining its operational temperature. The same trend can be seen in the case of blue line that represents the evaporator temperature when it rises to approximately 0°C. The Fig. 2. b illustrates the heat rejection capacity of the condenser in the two-stage heat pump system over time. Initially, the capacity experiences a rapid increase, reaching approximately 5 kW within the first 200 seconds. After this sharp rise, the capacity stabilizes around 5 kW, indicating that the system has reached a steady-state operation.

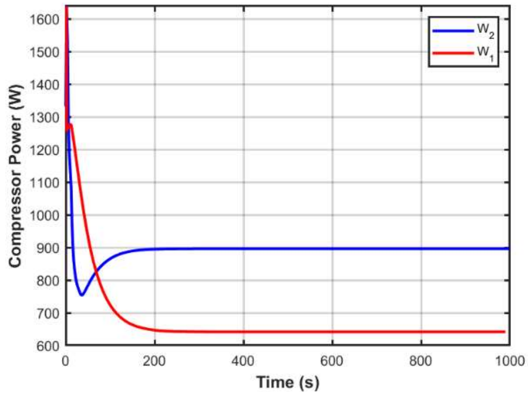

Fig. 3. Compressor power consumption over time for the low and high-pressure stage.

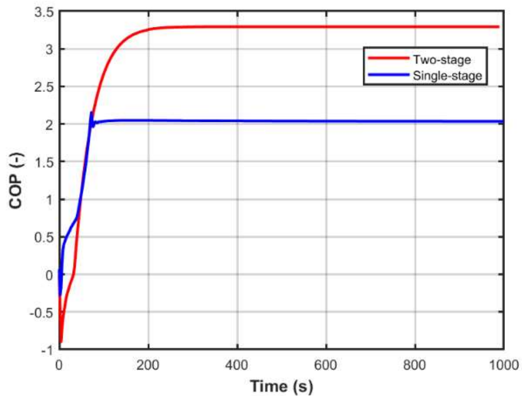

Fig. 4. COP Comparison over time for two-stage and single-stage heat pump systems.

The Fig.3 displays the compressor power consumption over time for both the low-pressure stage (W_1) and the high-pressure stage (W_2) in a two-stage heat pump system. Initially, the power consumption for the low-pressure stage (red line) peaks sharply and then rapidly decreases to stabilize at 0.641 kW within the first 200 seconds. In contrast, the power consumption for the high-pressure stage (blue line) also stabilizes at a value of around 0.896 kW within the same timeframe. The stabilization of both power consumptions indicates that the system reaches a steady-state operation after the initial transient phase, with the high-pressure stage consuming slightly more power than the low-pressure stage. Fig. 4 illustrates the COP of both two-stage (red) and single-stage (blue) heat pump systems over a period of time. The two-stage system achieves a higher COP, stabilizing around 3.29, whereas the single-stage system stabilizes around 2.04 showing the two-stage system is more efficient in transferring heat compared to the single-stage system in the dynamic mode.

5. CONCLUSIONS

This study presented a dynamic simulation of a two-stage air-to-air heat pump system using R1234yf as the refrigerant, modeled with OpenModelica. The performance of the two-stage system was compared to a single-stage heat pump under dynamic operating conditions. The results demonstrated that the two-stage heat pump achieves a higher COP compared to the single-stage system, highlighting its superior efficiency. To further enhance the COP of the two-stage system, we actively controlled the intermediate temperature, maintaining it around 31°C. Additionally, the condenser temperature was consistently controlled at 65°C in both configurations. The detailed analysis of compressor power consumption and heat transfer dynamics provided valuable insights into the operational advantages of the two-stage system. Future work will focus on experimental validation and further optimization of the system components and control strategies to enhance its practical implementation.

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