Abstract

The growing need to improve energy efficiency and reduce greenhouse gas emissions has intensified interest in technologies capable of utilizing low temperature waste heat sources. Thermally driven refrigeration systems represent a promising alternative to conventional electrically powered units, as they can provide cooling with minimal primary energy consumption. Within this group, the ejector refrigeration systems (ERS) offer particular advantages due to their simple mechanical design and compatibility with natural refrigerants. However, the performance of conventional fixed-geometry ejectors is highly sensitive to varying operating conditions, which limits their application in waste heat recovery systems characterized by variable heat source and ambient temperatures. This thesis presents a numerical investigation of an ultra-low-grade waste heat-driven ERS equipped with a variable geometry ejector (VGE) using the natural refrigerant propane (R290). The work addresses the limitations of fixed-geometry ejectors by studying a controllable spindle-based ejector capable of adapting to fluctuating ambient temperatures and load conditions. An experimental campaign confirmed that the R290 VGE can provide reliable mass entrainment ratio control by changing the effective motive nozzle throat area. The Computational Fluid Dynamics-based (CFD) performance maps were used as a basis for two Reduced Order Models (ROM): a baseline pressure-specific enthalpy model, and a generalized pressure-ratio and inlet temperature model. Both approaches were able to reproduce the CFD results with an error below 1% and were implemented in Dymola for dynamic ERS simulations. System-level simulations using weather data from three climatic zones and three industrial waste heat profiles showed consistent VGE performance gains compared to a system utilizing fixed ejectors, with daily-averaged coefficient of performance (COP) improvements of up to 52% and cooling capacity increases of up to 13%. The VGE-based ERS showed the highest benefits in hot climates with high daily temperature variability, where spindle control provides continuous on-design operation. The generalized ROM was also applied to the analysis of ERS with alternative refrigerants. The ERS with R1270 utilizing R290 VGE delivered up to 21% higher cooling capacity and 10% COP improvement related to the system utilizing R290, while other R290-based blends showed comparable or lower performance, indicating a need to expand the ROM operational envelope or re-design the ejector for other refrigerants. The thesis confirms that a single VGE can replace multiple fixed ejectors, enabling efficient, flexible cooling driven by ultra-low-grade waste heat.