Abstract

Carbon dioxide and other greenhouse gases produced from various industrial processes in the form of waste heat are significant contributors to environmental pollution and climate change. Reusing industrial waste heat is one way to address this existing issue. This thesis aims to develop a methodology to attain maximum energy output at the lowest investment cost, using Organic Rankine cycle (ORC) technology without effectively impairing the thermal efficiency of the industrial process. A suitable simulation method for different ORC models has been established, and in-depth analyses have been performed. An attempt is made to define the most efficient cycle in terms of cost-effectiveness and energy generation for a given waste heat source in an energy-intensive industry.

In India, there is a scarcity of literature regarding the potential of waste heat recovery. This thesis has attempted to fill in this gap by, holistically, studying the possible degree to which low-grade waste energy can be used in the Indian commercial and domestic industries (especially in the cement, iron, steel, and glass sector) to meet high energy demands. Three major research fields can be defined: the concept and estimate of waste heat in energy-intensive industries and the waste heat to power generation in such industries. An ORC system for any specific heat source with suitable working fluid and operating conditions is then determined. Additionally, this thesis also discusses the dynamics of the waste heat processes of ORC.

Based on data collected from related plants, a comprehensive analysis has been undertaken to identify a significant scope for recovering energy from low-grade waste heat, especially in India's cement, iron and steel, and glass sectors. A distinction is made between avoidable and unavoidable waste heat. Importantly, it is found that the iron and steel industries provide a maximum power production potential of 66.5 TWh by utilizing its waste heat.

A multi-objective optimization (NSGA-II) is developed, and thermodynamic and techno-economic optimization are carried out from a choice of 52 working fluids for ORC and RORC systems. Further, optimal compromised solutions are obtained from Pareto frontiers (as obtained from NSGA-II) by assigning a normalized weighted score to every point while selecting the minimum value point for each of the 52 potential working fluids. The efficiency of the cycle and total plant construction costs are calculated based on the selected optimal solution. Notably, the results show that benzene and toluene exhibit superior performance among the fifty-two selected working fluids for the pre-selected cycle's thermodynamic parameters. The result also includes the calculated static investment payback period for these fluids. The key objective of this study is to develop a code that finds the optimum power output from various working fluids based on user-defined variables. The graphical user interface (GUI) is designed in MATLAB® and is combined with Cool prop and Python language. The program is already loaded with 267 working fluids. Using the MATLAB® solver, the expected result is initiated with the program's key code. This work delivered a code that finds the optimum power output from various working fluids based on user-defined variables.

This thesis also covers the coupling of the ORC and CES systems. Additionally, it discusses the dynamics of waste heat processes of ORC by implementing three different control schemes. The results indicated that the RORC system with toluene as a working fluid is the optimum choice for the CES system with four stages of compression. This work also presents a case study using the waste heat data of a typical coke-oven plant where a steady-state simulation of the ORC system has been developed in Aspen Hysys®, and the result is validated using experimental data from the literature. 52 different working fluids are evaluated for power generation parameters based on the first law of efficiency, purchase equipment cost, and static investment payback period after validation of the ORC models. It was observed that the cycle efficiency from the working fluids Butane (11.94 %, 21.38%), Heptane (13.67%, 25.21%), Hexane (13.71%, 24.36%), Isopentane (12.67%, 22.8%), Neopentane (11.32%, 22.03%) and Toluene (16.06%, 25%) are comparatively higher for both ORC and the RORC systems. Further, cycle efficiency of the R134a (10.42%, 19.25%) and R245fa (12.06%, 21.03%) are comparatively lower for both ORC and the RORC systems. As regards the RORC system, all hydrocarbons were performing better than CFCs as working fluids. Lastly, the thesis provides an open-source integrated simulation platform that can be useful for future researchers and industry users to estimate the waste heat recovery potential based on the user-defined variables.

Keywords: Low-grade heat source, Exergy, Process integration, Energy efficiency, Heat recovery, Organic Rankine Cycle, Working fluid, Thermal energy management.