Abstract ESCAPE:

A bi-level mathematical approach for optimal synthesis of industrial heat pumping systems

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Industrial waste heat is abundant and represents significant energy inefficiency for many processes. With increasing emphasis on improving industrial energy efficiency, heat pumping systems (including refrigeration) offer a solution by valorizing low-temperature waste heat. Optimization of industrial refrigeration and heat pump systems attempts to reach the cost-optimal configuration of equipment (compressors, evaporators, etc), the sizes, operating conditions (pressures levels, temperatures), and working fluids. The nature of the problem structure is a mixed integer non-linear programming (MINLP) problem which has traditionally been solved by relaxing either the integer constraints or the nonlinearities to formulate a nonlinear (NLP) or mixed-integer linear (MILP) problem.

The first comprehensive methodology was presented by Shelton and Grossmann in the form of an MILP superstructure [1,2]. Their work is based on a discrete set of temperature levels and a specified working fluid. Other authors based their formulation in the linear domain [3,4] by modifying the MILP proposed in [1] to incorporate economizers and working fluid selection in their formulation [4]. An NLP approach was chosen by [5,6] based on lumped temperature intervals by presetting the number of compression stages (pressure levels) and the working fluid.

A novel heat pump superstructure is proposed in this work which attempts to address the shortcomings of previous work. It incorporates two new features compared to previous studies: (i) sub-cooling before expansion in addition superheating to (which has already been incorporated), (ii) intermediate cooling between compression stages by heat exchange and between expansion stages in addition to mixing with pre-saturators. The MINLP superstructure is solved using a bi-level approach [7] in which the problem is decomposed into a slave MILP sub-problem and a nonlinear master problem. The master level uses a genetic algorithm to set the non-linear decision variables (temperatures, pressures, working fluid) while the slave sub-problem selects the active equipment stages and their sizes. The MILP generates a list of streams which allows heat exchanger network synthesis in a second slave optimization though this procedure is not yet included.

The superstructure was applied to a set of MILP literature cases and it is shown that the relaxed MILP sub-problem compares well; furthermore, the full bi-level approach generates improvements around 15% compared to the literature optimal scenario with respect to the total annualized cost. Additionally, an industrial-scale problem (a dairy plant) was studied as an example case. The application of the proposed methodology in this case leads to a 10% reduction in electricity consumption with an investment payback time under 3 years.

[1,2]M. R. Shelton, 1986, I & II. [3]K. Holiastos, 2002. [4]S. Vaidyaraman, 1999. [5]T. R. Colmenares, 1989. [6]T. R. Colmenares, 1987.[7]C. Weber, 2007. [8]NIST, 2013.