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FINNED-TUBE HEAT EXCHANGER SIMULATION PROGRAM WITH REFRIGERANT CIRCUITRY OPTIMIZATION CAPABILITY

PROGRAM SYMULACYJNY DLA OŻEBROWANYCH WYMIENNIKÓW CIEPŁA Z OPTYMALIZACJĄ UKŁADU PRZEPLYWU CZYNNIKA

ABSTRACT

This paper presents an interactive finned-tube evaporator and condenser design program, EVAP-COND (ver. 3), which incorporates a computational intelligence module, ISHED (Intelligent System for Heat Exchanger Design), for optimization of refrigerant circuitry. This paper presents ISHED's design, its function, the parameters controlling an optimization run, selected examples of ISHED experimentation, and EVAP-COND/ISHED integration.

1. INTRODUCTION

Increased concerns about climate change and escalating energy costs have emphasized the importance of air-conditioning and refrigeration systems with high coefficients of performance (COP). A vapor-compression system's COP is strongly influenced by the effectiveness of heat exchangers it employs. Optimization of heat exchangers is desirable to improve their effectiveness and reduce their production cost. For finned-tube heat exchangers, one of the most important design parameters is the sequence in which the tubes are connected to define the flow path of refrigerant through the coil, i.e., the refrigerant circuitry. Several studies have indicated the importance of proper design of refrigerant circuitry on heat exchanger and system performance, e.g., [1-3].

The refrigerant circuitry determines the distribution of refrigerant through the heat exchanger, which impacts the refrigerant mass flux, heat transfer, pressure drop,

and saturation temperature in each individual tube. Different refrigerants may benefit from different refrigerant circuitry architectures because of the variations in their thermophysical properties. An optimized refrigerant circuitry is one that finds the best match between refrigerant and air properties and flow parameters at each location to maximize the total heat exchanger capacity.

The refrigerant circuitry is typically determined after the heat exchanger's outside dimensions, tube diameter, tube and fin spacing, and heat transfer surfaces are selected. Currently, circuitry design is primarily driven by engineer's experience aided by supplemental heat exchanger simulations, which are performed manually. Designing an optimized refrigerant circuitry is particularly difficult if the airflow is not uniformly distributed over the coil surface. In such a case, the design engineer may be tempted to assume a uniform air velocity profile, which will result in capacity degradation [4].

Several heat exchanger simulation models, public-domain and proprietary, account for the refrigerant circuitry and can be used in the refrigerant circuitry optimization, e.g., EVAP-COND [5]. However, the optimization process requires that a design engineer performs these simulations manually, each time specifying different candidate circuitry architectures. Since the number of possible circuitry architectures is extremely large, manual simulations can examine only a small portion of viable circuitries while a fully exhaustive automated search is not feasible. A heat exchanger consisting of n tubes will have $n!$ possible circuitries considering designs that are limited to one inlet and one outlet. The true field is much larger, since it is possible to have multiple inlets and tubes that deliver refrigerant to more than one tube; for example, a heat exchanger with 36 tubes will have approximately $2 \cdot 10^{45}$ possible architectures. A guided automated search method, as implemented in ISHED (Intelligent System for Heat Exchanger Design, [6]), is therefore an attractive avenue for determining the optimal circuitry design. For this reason, the new release (ver. 3.0) of EVAP-COND will incorporate ISHED as a circuitry optimization option.

2. ISHED

2.1. Genetic Algorithms and ISHED

Genetic Algorithms (GAs) are general-purpose search algorithms that are based on natural selection and natural genetics. GAs were developed in 1975 by [7] whose original interest was to study the phenomenon of adaptation in natural system and to develop software that would apply the important adaptation mechanism. Since then, GAs have been used in various fields and proven to provide robust search in complex spaces [8]. Examples of application of GAs in the HVAC&R field are given in [9-11].

The optimization module, ISHED, incorporated into the newest version of EVAP-COND, has several features that are common for all GA programs, but it also implements a few unique concepts. Consistent with a conventional GA program, ISHED operates on one generation (population) of refrigerant circuitries at a time. A population consists of a given number (determined by the user) of circuitry designs. Each member of the population is evaluated by a heat exchanger simulator, EVAP-COND, which provides each member's capacity as a single numerical fitness value. The designs and

their fitness values are returned as an input for deriving the next generation of circuitry designs. Hence, the implemented process is iterative, and it is repeated for the number of generations specified by the user.

The major difference between a basic GA program and ISHED is that ISHED uses two independent modules, a Knowledge-based Evolutionary Computation Module and Symbolic Learning Evolutionary Module, for generating new refrigerant circuitry architectures. The knowledge-based module does not use the typical GA operators (crossover, mutation) but rather eight refrigerant circuit-specific operators (split, break, combine, insert, move-split, swap, intercross, new-source). In addition, these operators are not random, as in conventional GA, but domain knowledge-based, i.e., they only perform changes that are deemed suitable according to the domain-knowledge.

The symbolic learning-based module generates new individuals (designs) in an entirely different way, by hypothesis formation and instantiation [12]. When applied, it divides the members of the current population into three classes based on their fitness values (cooling capacity); “good”, “bad”, and “indifferent”. The “good” and “bad” classes contain members of the population whose fitness are in the top and bottom 25 % of the current generation’s fitness range, respectively. Then, the module examines the characteristics of both well- and poorly performing designs, and creates hypotheses in the form of attributional rules that characterize the better-performing architectures. These rules are applied to generate the subsequent population of designs. A more complete description of ISHED, including information on implementation of the Knowledge-based Module and Symbolic Learning Module, is presented in [6].

2.2. Optimization Studies using ISHED

We performed analytical experimentations with ISHED to test its capability to optimize refrigerant circuits for different refrigerants and for non-uniform air distribution at the heat exchanger inlet. In all cases, ISHED generated circuitry designs that were as good as or better than those prepared manually. In a study using six refrigerants of

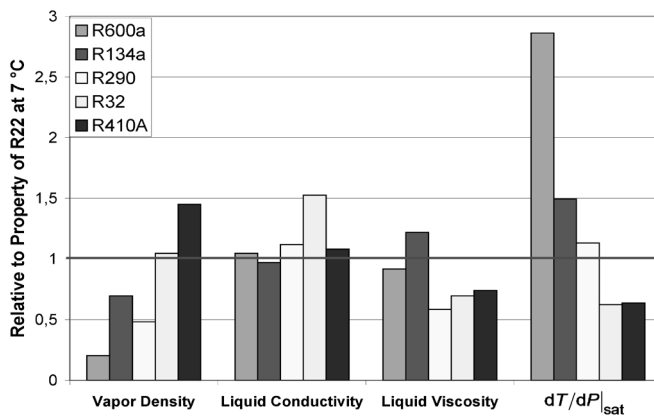


Fig. 1. Refrigerant properties at 7 °C for studied refrigerants.
(T- temperature; P-pressure; sat – saturation)

vastly different thermophysical properties (Figures 1 and 2), the evaporator capacities for refrigerant circuits generated by ISHED were better than those for manually generated 1, 1-2, 2, 3, and 4 circuit designs (Figure 3) [13]. As an example, Figure 4 shows the manually generated and ISHED-generated designs for R600a. Similar results were obtained in a condenser study for the same six refrigerants [14].

Another very promising facet of these studies is ISHED's ability to optimize a circuitry design for non-uniform inlet air distribution. It is extraordinarily difficult to determine a well suited circuitry design for this situation because of the problem's inherent complexity, even for the most experienced heat exchanger designers. ISHED, however, has the ability to learn what features assist and impede performance for the

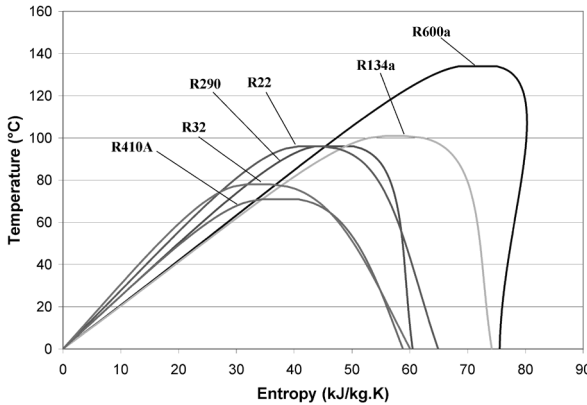


Fig. 2. Temperature - Entropy diagram for studied refrigerants. (Entropy is referenced to the liquid entropy at 0 °C.)

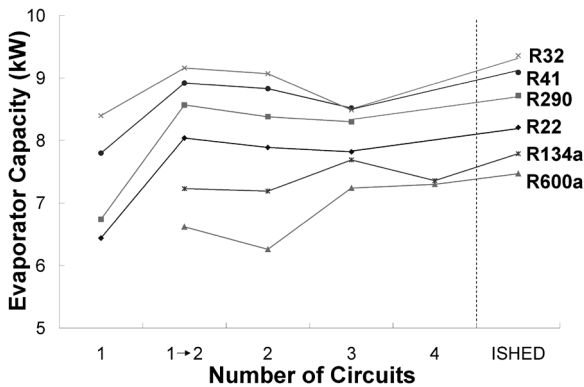


Fig. 3. Evaporator capacities for manually generated and ISHED-optimized circuitry [13]. (1→2 designates one inlet circuit splitting in two outlet circuits.)

configuration at hand, regardless of how complex air flow characteristics may be. Figure 5 shows the decline in capacity of a heat exchanger that was designed for uniform air flow, if it were subject to non-uniform air distribution. This figure illustrates that capacity lost because of maldistributed air can be significantly recovered through ISHED circuitry optimization when performed for a given air distribution [14].

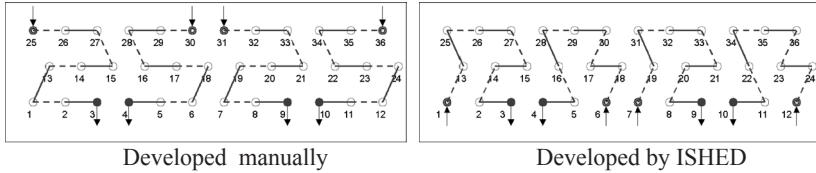


Fig. 4. Manually developed and ISHED-optimized 4-circuit designs for R600a [13]. (Arrows indicate refrigerant inlet and outlet tubes.)

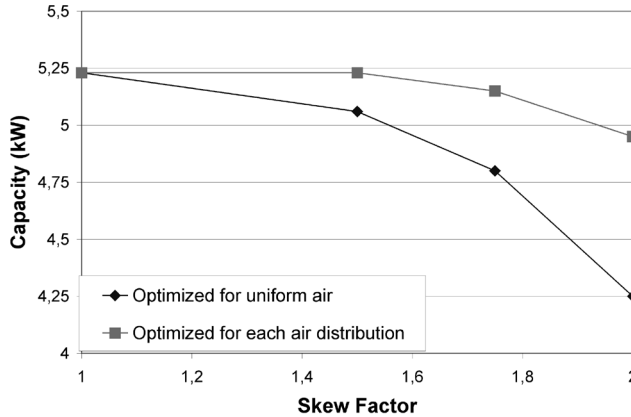


Fig. 5. Recovery of lost capacity due to one-dimensional, linear air maldistribution through ISHED optimization [14]. “Skew Factor ” characterizes the air distribution (ratio of maximum air velocity to the average air velocity).

3. ISHED IMPLEMENTATION WITHIN EVAP-COND

The ISHED optimization module is embedded in the EVAP-COND ver. 3.0 package and it is accessible from the main EVAP-COND window through the ‘Circuitry Optimization’ pulldown menu.

3.1. Pre-processing

Input data for an ISHED optimization run consists of the same data needed to execute a simple simulation run by EVAP-COND (inputting refrigerant circuitry is optional) and some additional data defining how the optimization process is to be

carried out. The set of data describing the geometry of the heat exchanger, heat transfer surfaces, and refrigerant are the same as those specified within the EVAP-COND window. Once these items are specified, the user enters the ISHED operating conditions followed by the optimization process control parameters in the 'ISHED Control Parameters' window. Here the user can specify certain design rules and constraints for the allowable circuitry designs, the number of circuitry architectures in each generation, the number of generations examined in the optimization run, and some other advanced parameters. The user also has the option to specify "seed" files. When using this option, the user-specified circuitry designs (which may be generated by the user or results of previous optimization runs) will be included in the generation of as starting designs along with the random ISHED-generated designs

3.2. Optimization run

Once all of the input has been entered, the user can initiate the execution of the optimization run. The optimization run may take a considerable amount of time depending on the computer's speed, the size of the heat exchanger, the specified refrigerant, and the entries for the ISHED control parameters. A typical optimization run will last several hours; a computer with a multiple core processor will complete an optimization run considerably faster than one with a single core processor of comparable clock speed.

Throughout the execution, the program creates and updates several files containing intermediate results. Most importantly, the program maintains a log file that contains the top ten performing circuitry architectures and updates it each iteration cycle throughout the optimization run. Also, a log file of with all optimization steps from the beginning of the execution onwards, called `ishedtrace.log`, is continuously updated. A user can check on the progress during program execution and, in a case of program instability, can recover useful data from these files to prevent loss of information during a failed optimization run.

It is also important to keep in mind that the evolutionary methods employed within ISHED have some degree of randomness, as opposed to calculus-based methods, which produce the same results each time. For this reason ISHED will not produce the same architecture design during the course of different optimization runs. The results of one optimization run may therefore fare slightly better or worse than another. Hence, it is practical to repeat an optimization run a few times and select the best design.

3.3. Post-processing

At the end of a successful optimization run, the program displays a message indicating completion along with the highest heat exchanger capacity obtained as a result of the run. The user can access the ten best performing circuitry architectures within EVAP-COND by navigating to the ISHED Results folder. Most often, the user will find it necessary to modify ISHED-generated circuitry architectures to accommodate manufacturing constraints; although the user has the option to limit ISHED's exploration with a few design rules and constraints, real world constraints are often much more involved. For this reason, it is very likely that the best performing designs, as

returned by ISHED, will not appear to be realistic upon first look, and therefore will require a certain level of manual post-processing. During the post-processing effort, the user will have to “clean” the circuitry (i.e. rerouting tube connections to remove crossovers, long return bends, etc.), while preserving the general design architecture. Figure 6 shows an optimized evaporator circuitry architecture produced by ISHED for a highly non-uniform air flow distribution, and a similar architecture that is the result of manually post processing the ISHED design. The performance of the heat exchanger did not change significantly during this post processing effort.

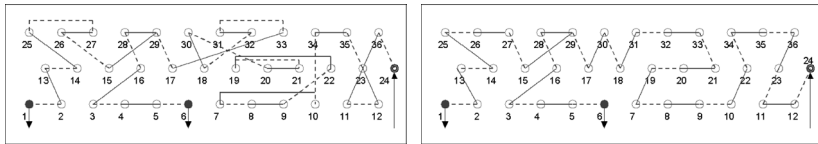


Fig. 6. ISHED generated circuitry results, before (left) and after (right) post processing.

4. SUMMARY

In this paper we presented the computational intelligence-based optimization module, ISHED, which is incorporated into version 3.0 of EVAP-COND. ISHED optimizes the performance of a finned-tube heat exchanger by determining the best refrigerant circuitry to suit the refrigerant, air, and material properties; air and refrigerant flow rates; and air distribution. Inclusion of ISHED expands the utility of EVAP-COND beyond conventional features of a heat exchanger design tool.

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