TUBE BUNDLE OPTIMIZATION FOR CHILLERS USING A MODIFIED DYNAMIC PROGRAMMING TECHNIQUE

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ABSTRACT

A preliminary stage in the design of chillers is allocation of heat and mass transfer surface area between the various components. The allocation is based upon transport performance, pressure drop, component size and, last but not least, cost considerations. This paper presents a technique to optimize the area distribution, using a variation of dynamic programming. Absorption chillers with shell-and-tube components are considered for illustrative purposes, but the technique can be applied to any power or refrigeration system and component configuration.

KEYWORDS

Chiller, Absorption, Design, Optimization, Cost, Dynamic Programming.

1. INTRODUCTION

In today's highly competitive global environment, product cost plays a very important role in profit realization. Minimization of cost at a given performance level is critical to the overall success of a design. The concept design phase of any chiller product includes the determination of component surface area that would deliver the desired performance under standard operating conditions. Generally, the same performance can be achieved with different surface area distributions between the components, within design constraints. However, each distribution results in a different product cost. To find the distribution yielding the lowest cost, experiential methods applied selectively to component pairs are used typically. Mathematically rigorous techniques are conspicuously absent from the design process. This has provided the motivation for the present work.

The goal of this work is to develop a generalized algorithm for surface area allocation that yields minimum product cost. As with any optimization problem, this requires the definition of an objective function and a combination of equality and inequality constraints [1]. For chiller design, the objective function to be optimized then translates to a cost function to minimized. The formulation of the cost function relies primarily on *material* cost data, for concept design. The constraints of the problem are imposed by performance requirements and operating limits. In addition to the cost function and constraints, prior knowledge of *component* performance characteristics, empirical or theoretical, is necessary. Finally, a thermodynamic system model incorporating these characteristics and the cost function serves as a vehicle for the optimization process. This model could be a derivative of the selection or performance prediction model developed for similar product [2]. A suitable optimization technique then needs to be implemented.

2. COST FUNCTION

Optimization of chiller design can be carried out at a given chiller efficiency. That is, the optimized design delivers the desired capacity at fixed operating costs. Thus, for the optimization, one is only interested in capital or first costs. The first cost itself can be defined as:

$$FC = FFC + VFC \quad (1)$$

The fixed first cost does not vary with the design variables. For a conceptually similar chiller of different capacity, this component of the first cost is constant. A typical value for a small two-stage steam-fired unit is \$192/ton. Since the objective of the optimization is first cost minimization,

$$Min(FC) = Min(FFC + VFC) = Min(VFC) \quad (2)$$

Hence, minimization of the variable first cost alone, subject to the necessary constraints, will yield the best combination of design variable values.

The variable first cost is defined as the sum of the tube material and assembly costs and the shell material cost. The latter changes with tube bundle dimensions, in terms of the material content of the shell wall. There are other variable costs, e.g. those relating to the labour amount as a function of component size / aspect-ratio, but these have been treated as negligible for the present exercise. Thus, the objective function for the chiller optimization problem is:

$$VFC = \sum \begin{pmatrix} Tube\ Material\ Cost + \\ Tube\ Assembly\ Cost + \\ Shell\ Material\ Cost \end{pmatrix} \quad (3)$$

where each of the above variable costs is a function of the following independent variables: tube/chiller length (L), tube diameter (D), number of tubes (N_{tubes}), number of columns or rows ($N_{columns}$ or N_{rows}) and number of passes (N_{passes}). These are the design variables that initiate the development of a typical shell-and-tube chiller.

3. DESIGN VARIABLES

Each of the above independent variables has impact on chiller/component performance, albeit via different mechanisms. Naturally, all affect capacity and efficiency (COP) and hence cost. However, tube length does so via surface area, tube count and diameter via surface area and the inside heat transfer coefficient, number of columns (or rows) via the outside heat transfer coefficient, and number of passes via the inside heat transfer coefficient alone. Tube length, diameter, count and number of passes also directly impact cooling- or chilled-water pressure drop via the inside friction factor. Finally, tube count and number of columns (or rows) determine bundle/component sizes, for given tube spacing, and hence overall width and height of the chiller.

4. OPERATING CONSTRAINTS

The optimization of any practical objective function is usually subject to certain constraints or limiting conditions. These can be equality or inequality constraints. In the minimization of the cost function defined above, chiller operating constraints play a crucial role. Desired capacity and COP would be the equality constraints, e.g.

$$\begin{aligned} &Capacity = 1000\ tons \\ &COP = 0.68 \end{aligned} \quad (4)$$

while chilled- and cooling-water pressure drops and velocities, evaporator leaving approach temperatures and programmable control-system variables, and unit footprint and height would be inequality constraints, e.g.

$$\begin{aligned} &\Delta p_{cooling\ water} \leq 9.1\ m\ (30\ ft)\ of\ water \\ &H < 3.7\ m\ (12\ ft) \end{aligned} \quad (5)$$

Programmable controls for water-LiBr absorption chillers include crystallization and corrosion protection, refrigerant purity (with respect to salt) and energy and solution flow modulation. The case studies presented in the Results & Discussion section will illustrate the formulation of the optimization problem in greater detail.

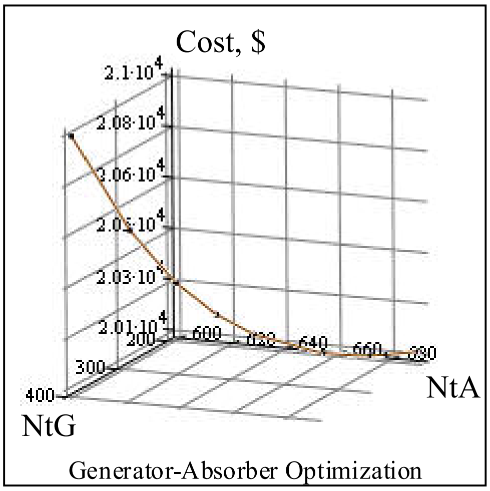
5. MODIFIED DYNAMIC PROGRAMMING FOR CHILLER DESIGN

Dynamic programming is a method of optimization applicable to staged processes, or to continuous functions that can be approximated by staged processes [1]. The algorithm to arrive at an optimal configuration or design involves establishing optimization routines for subsections of the problem. The results of the optimization for the subsections are used in succeeding evaluations, and no path between the subsections originates from a non-optimal (subsection) configuration.

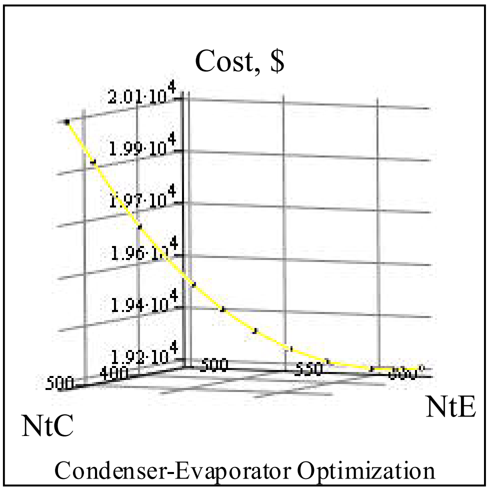
To demonstrate the above, consider the single-stage absorption chiller. This has four primary shell-and-tube components: generator, condenser, evaporator and absorber. A typical selection model for such a chiller uses geometric (described above) and working-fluid – related (solution flow rates) design variables as inputs to predict performance, i.e. these have fixed values in the model. If a given chiller capacity is desired, at a certain thermodynamic efficiency, *these* become inputs and a pair of design variables can float. In this work, the tube count in one of the components and the solution flow rate constitute the floating pair. Once the flow rate necessary for the desired COP is tentatively established, via model runs of the initial configuration, the problem breaks down into as many subsections as there are component-pair combinations. That is, for each component in each pair, the optimum tube count yielding the desired performance at the lowest chiller variable first cost is sought, within the operating constraints described above. This is done by increasing (or decreasing) the tube count for one of the components in a pair and decreasing (or increasing) that for the other until a minimum chiller cost is attained.

When a given component pair is optimized, the algorithm moves on to the next pair or subsection of the problem with the latest (optimum) tube counts from the previous subsection, as per the principle of dynamic programming (Stoecker, 1989). The cost minimum reached at the end of each subsection is of course a *constrained* minimum. Figure 1 shows each subsection optimization for a 400-ton single-stage absorption chiller, unconstrained for illustrative purposes. Note the diminishing minimum cost from one plot to the next (the minimum in one plot is the maximum in the next). However, the cost calculated at the end of a single *cycle* of subsections is not necessarily the lowest cost possible. This is because the optimization is carried out piecemeal, a component pair at a time. Thus, the optimum tube counts obtained at the end of the first subsection, for the initial tube counts in the remaining components, might not be optimal with the latest tube counts in these components. The end of one cycle then serves as the beginning of another, and the same sequence of subsection optimization is repeated with the constantly evolving tube counts. The iterations continue until the chiller variable cost does not change in excess of a user-defined cost tolerance. When this point is reached, the resulting tube counts in the different components yield the final bundle configuration of the chiller. The iterative nature of the algorithm renders it a *modified* dynamic programming technique.

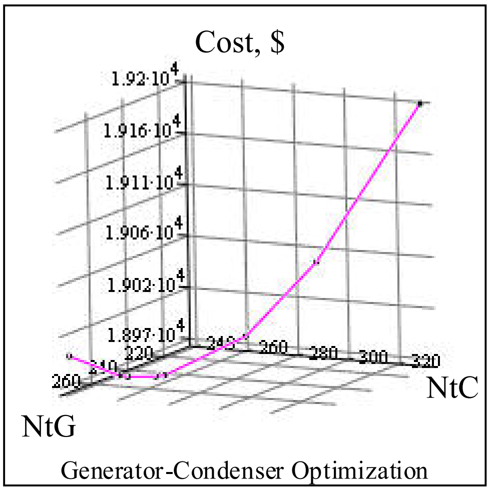
For this work, the required thermodynamic model was developed using TK Solver for Windows [3]. The constrained dynamic programming was incorporated into a Visual Basic interface needed for this model [4].



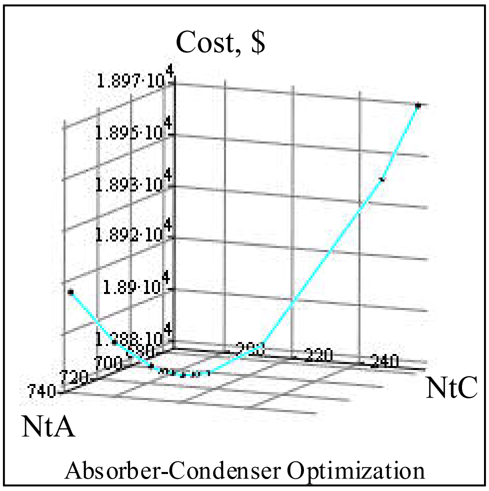
(NtG, NtA , Cost1)



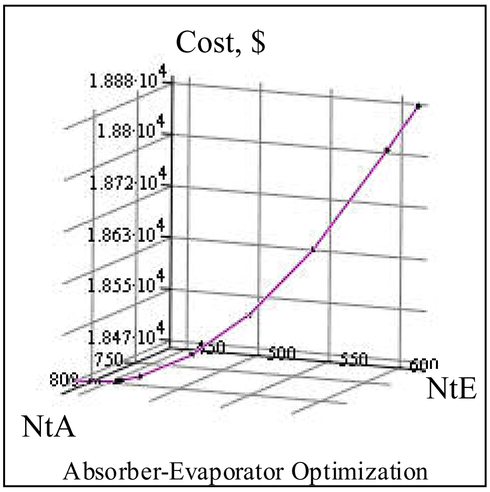
(NtC, NtE, Cost2)



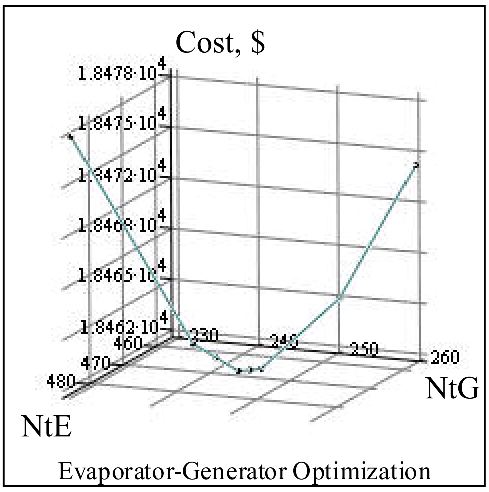
(NtG, NtC, Cost3)



(NtA , NtC, Cost4)



(NtA , NtE, Cost5)



(NtE, NtG, Cost6)

Figure 1: Subsection (Component-Pair) Optimization

6. COMPONENT PERFORMANCE PARAMETERS

As mentioned, the optimization algorithm relies on a model or engine for cycle calculations. The cycle calculations in turn require component performance predictions. For shell-and-tube components, these typically depend on the inside (with respect to the tubes) heat transfer coefficients and friction factors, and outside heat and/or mass transfer coefficients. The in-tube characteristics are obtained from standard correlations for smooth and enhanced tubes [5, 6], while the outside transport is from empirical correlations based on lab data [7]. In-house data has been used in the case of the latter because reliable standard correlations are not available for the typical operating range of the tube bundles.

7. DESIGN PARAMETERS

Some design variables must be held fixed during execution of the optimization algorithm, making them design parameters. For the case studies presented here, all the independent variables identified above are treated as parameters, except tube counts. In addition, the cooling water flow configuration (series or parallel, with respect to the absorber and condenser), component layout (side-by-side or over-under), and in-tube fouling are also assumed.

For absorption chillers, solution-to-solution heat exchangers play an important role in the overall performance. In this work, the performance prediction model treats the heat exchanger effectiveness as a parameter, although this component could also be included in the optimization via its tube or plate count and a corresponding heat exchanger model. The fixed-effectiveness heat exchanger here, having a "frozen" design, contributes only a fixed cost.

The above discussion also applies to the direct-fired generator of two-stage absorption units and its combustion efficiency. In the case of vapour-compression chillers, the compressor efficiency could be handled in the same manner, unless a compressor model or map was integrated into the performance prediction engine. Ideally, the inter-relationship between geometry, efficiency and cost for each of these components should be incorporated into the engine to "thaw" its design. Thus, the chiller optimization presented in this paper assumes a fixed efficiency/cost, dictated primarily by speed concerns and lack of detailed models, for certain components.

8. CONVERGENCE CRITERIA

To arrive at the minimum unit cost during (subsection) optimization between two components, a variant of the bisection technique was used [8]. The convergence criterion forced the absolute increment in cost at the end of a tube-count combination to be within 0.01% of that from the previous tube-count combination, for the given component pair. A second minimum-cost convergence criterion was required, for the iterations of the outer loop or subsection cycles. Thus, when all component pairs had been individually optimized, a comparison was made between the unit cost at the end of the cycle and that before it (i.e. the cost at the end of the previous cycle). In this case, the negative increment had to be within 0.1% of minimum (final) cost from the previous iteration. Both convergence criteria are user-defined and can be modified to suit the cost/tube-count tolerance of the application.

9. RESULTS & DISCUSSION

The single-stage absorption chiller has four primary components and hence six combinations for optimization. A somewhat realistic configuration, shown in Table 1, was selected as baseline [9]. As the first step in a new chiller design, some manipulation of L, D, $N_{columns}$, N_{passes} and cooling water flow circuitry was required to arrive at this configuration. An efficiency level (desired COP) was prescribed by fixing the solution flow rates and heat exchanger effectiveness at suitable values.

The optimized configuration results in a 3.5% cost reduction without compromising performance and violating operating constraints (imposed by the controls). This is also included in Table 1 for comparison, along with the operating limits. An increase in pressure drop in the process, resulting from a requirement to improve the in-tube heat transfer coefficient via higher Reynolds numbers to counter diminishing surface area, is acceptable as long as it is within the constraint "box" (here, satisfying an upper limit of 9.1 m or 30 ft of water).

The process of going from the baseline configuration to the optimized one is shown in Figure 2. The variable first cost of the former is represented by the leftmost diamond symbol, while that of the latter is represented by the rightmost diamond. The optimization algorithm goes from the generator-condenser to the condenser-evaporator and so on (inner loop iterations) until the variable first cost change across the optimization of each pair is within the predefined 0.01% tolerance, i.e. all six pairs are individually optimized. This constitutes the first outer loop iteration. Since the variable first cost at the end of this first cycle is not within the 0.1% tolerance (with respect to the initial variable first cost) set for the outer loops, the algorithm embarks upon a second outer iteration. As can be seen from Figure 2, the change in variable first cost across this cycle is well within the acceptable tolerance, yielding the optimized tube bundles.

Table 1: Comparison of Baseline and Optimized Configurations for a 1000-Ton Single-Stage Absorption Chiller (COP=0.68, Generator Solution Flow Rate=13.8 L/s (218 GPM), Tube Length=6.1 m (20 ft))

Parameter	Baseline	Optimized	Operating Limits
Cooling Water Pressure Drop	4.7 m (15.5 ft) of water	4.6 m (15.0 ft) of water	< 9.1 m (30.0 ft) of water
Chilled Water Pressure Drop	5.9 m (19.4 ft) of water	7.8 m (25.6 ft) of water	< 9.1 m (30.0 ft) of water
Condenser Tube Velocity	2.5 m/s (8.3 ft/s)	2.4 m/s (8.0 ft/s)	< 2.7 m/s (9.0 ft/s)
Absorber Tube Velocity	1.4 m/s (4.5 ft/s)	1.3 m/s (4.4 ft/s)	< 2.7 m/s (9.0 ft/s)
Evaporator Tube Velocity	1.8 m/s (5.9 ft/s)	2.2 m/s (7.1 ft/s)	< 2.7 m/s (9.0 ft/s)
Crystallization Margin	7.1°C (12.8°F)	6.7°C (12.0°F)	≥ 6.7°C (12.0°F)
Maximum Solution Temperature	102.4°C (216.3°F)	102.3°C (216.2°F)	< 165.6°C (330.0°F)
Evaporator Approach Temperature	1.1°C (2.0°F)	1.4°C (2.6°F)	< 2.2°C (4.0°F)
Number of Generator Tubes	330	329	-
Number of Condenser Tubes	200	206	-
Number of Evaporator Tubes	450	374	-
Number of Absorber Tubes	1010	1040	-
Variable First Cost	$37955	$36640	-

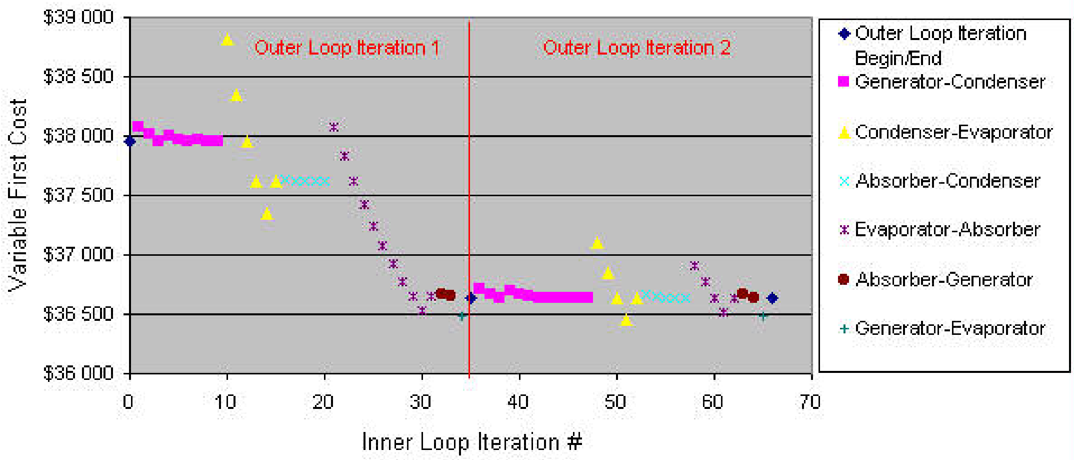


Figure 2: Path to Convergence for 1000-Ton Single-Stage Absorption Chiller Optimization (Outer Loop Criterion: -0.001 < (VFnew - VFprev) / VFnew < 0; Inner Loop Criterion: Abs(VFnew - VFprev) / VFnew < 0.0001)

As would be expected, the overall result is a monotonically decreasing cost function made up of segments of dramatically different slopes. A closer look at the inner loop iterations reveals discontinuity or "spikes" in the cost function between the optimization of one component-pair and the next. The more obvious instances of this are the condenser-evaporator and evaporator-absorber optimization. In the latter, for example, the number of additional, relatively expensive tubes in the evaporator accompanying a reduction of 10 tubes in the absorber for the same performance level results a jump in the cost. Such pairs are evidently more critical to the overall optimization than others, the cost function having a significantly steeper negative slope. Finally, the duration of optimization for a given pair (number of inner loop iterations) is indicative of how removed the bundles in that pair were from having optimum tube counts.

As mentioned earlier, the optimization algorithm was extended to include two-stage chillers, i.e. four more component combinations were added, relating the design of the new component (high-temperature generator) to that of the original four. A baseline configuration was established for the two-stage, steam-fired machine. This was a simpler exercise than the single-stage case, current two-stage chillers having already been developed. Thus, L, D, $N_{columns}$, N_{passes} and water flow circuitry similar to those in existing product could be used, i.e. very little pre-processing was required. Table 2 shows the baseline configuration. This time, the efficiency level was prescribed by fixing the solution flow rates and heat exchanger effectiveness*es* at typical values.

The optimized configuration results in a 8.9% cost reduction without compromising performance and violating operating constraints. The greater cost reduction relative to the single-stage case is indicative of the fact that the single-stage baseline was a relatively better design than that of the two-stage machine. The final two-stage configuration and the constraints are also included in Table 2 for comparison.

The process of going from the baseline configuration to the optimized one in this case is shown in Figure 3. Again, the variable first cost of the former is represented by the leftmost diamond symbol, while that of the latter is represented by the rightmost diamond. The same convergence criteria are used, i.e. 0.01% variable first cost change for the inner loop iterations and 0.1% change for the outer loop iterations. Based on the latter, again only two iterations were required, suggesting that the second outer loop iteration serves primarily as a double-check for convergence. In this case, the condenser-evaporator is not as critical to the overall optimization, but there is still great sensitivity to evaporator-absorber design.

All performance simulations were carried out for a chilled water supply temperature of 6.7°C (44°F) and a tower water entering temperature of 29.4°C (85°F). The optimization procedure was written in Visual Basic and executed as part of the chiller selection model on a Pentium-II, 233 MHz PC. The technique has been validated via some very successful absorption chiller designs at Trane (e.g. recent 975-1350 tons single-stage product).

Table 2: Comparison of Baseline and Optimized Configurations for a 500-Ton Two-Stage Absorption Chiller (COP=1.19, Generator Solution Flow Rate=6.3 L/s (100 GPM), Tube Length=5.5 m (18 ft))

Parameter	Baseline	Optimized	Operating Limits
Cooling Water Pressure Drop	7.4 m (24.4 ft) of water	8.0 m (26.4 ft) of water	< 9.1 m (30.0 ft) of water
Chilled Water Pressure Drop	4.6 m (15.2 ft) of water	8.7 m (28.6 ft) of water	< 9.1 m (30.0 ft) of water
Condenser Tube Velocity	1.2 m/s (4.1 ft/s)	2.5 m/s (8.3 ft/s)	< 2.7 m/s (9.0 ft/s)
Absorber Tube Velocity	1.6 m/s (5.2 ft/s)	1.3 m/s (4.4 ft/s)	< 2.7 m/s (9.0 ft/s)
Evaporator Tube Velocity	1.7 m/s (5.6 ft/s)	2.4 m/s (7.9 ft/s)	< 2.7 m/s (9.0 ft/s)
Crystallization Margin	12.4°C (22.3°F)	13.7°C (24.7°F)	≥ 11.1°C (20.0°F)
Maximum Solution Temperature	161.7°C (323.0°F)	160.3°C (320.6°F)	< 165.6°C (330.0°F)
Evaporator Approach Temperature	0.8°C (1.4°F)	1.2°C (2.1°F)	< 2.2°C (4.0°F)
Number of HT Generator Tubes	250	215	-
Number of LT Generator Tubes	350	330	-
Number of Condenser Tubes	200	100	-
Number of Evaporator Tubes	350	248	-
Number of Absorber Tubes	566	676	-
Variable First Cost	$32180	$29306	-

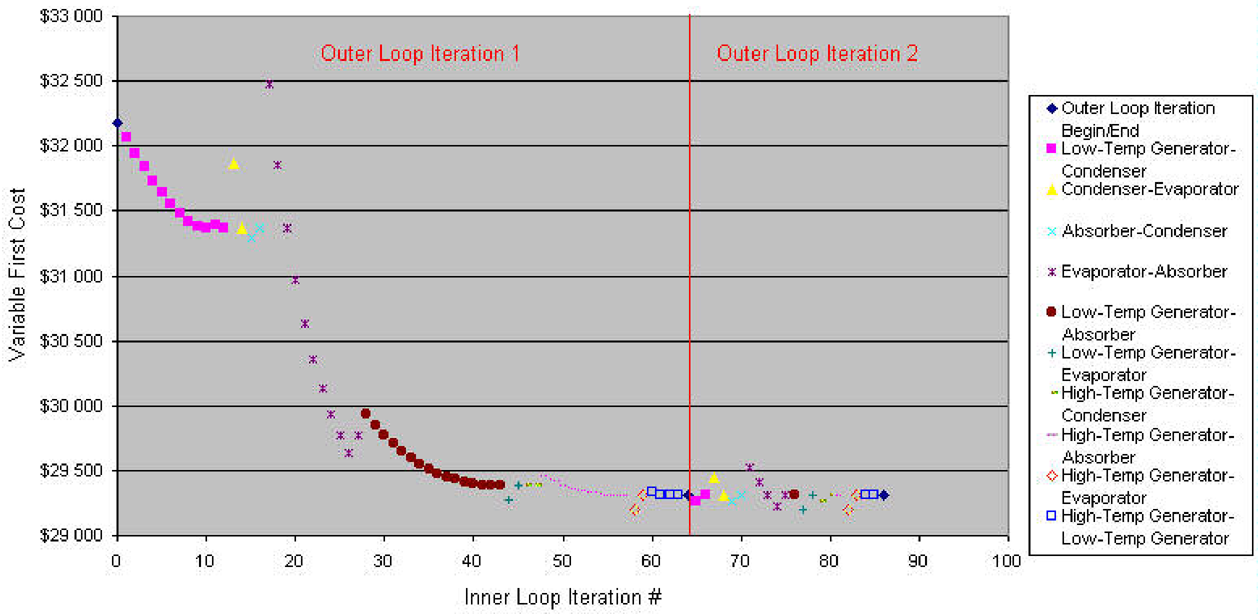


Figure 3: Path to Convergence for 500-Ton Two-Stage Absorption Chiller Optimization (Outer Loop Criterion: -0.001 < (VFnew - VFprev) / VFnew < 0; Inner Loop Criterion: Abs(VFnew - VFprev) / VFnew < 0.0001)

10. CONCLUSIONS

A mathematically rigorous tool has been developed for the design of water chillers. The tool is a variation of dynamic programming that is iterative and subject to constraints (chiller operating limits). Using water-LiBr absorption machines as the test premise, optimization of the tube bundles leading to minimum costs has been demonstrated. The procedure is exhaustive in that all pair combinations of the major chiller components are considered in the optimization. Depending on the tube types and associated costs, some component pairs have a greater impact on the optimization than others, e.g. evaporator-absorber. This design tool can be applied to other heat- and/or mass-exchange equipment employing tube bundles.

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NOMENCLATURE

Cost1, Cost6	Variable first cost at end of optimization of component-pair 1, 6
COP	Coefficient of Performance
D	Tube diameter
FC	First (capital) cost
FFC	Fixed first cost
H	Height of chiller
L	Tube Length
NtA	Number of tubes in absorber
NtC	Number of tubes in condenser
NtE	Number of tubes in evaporator
NtG	Number of tubes in generator
VFC	Variable First Cost
VFnew	Variable First cost after present iteration
VFprev	Variable First cost after previous iteration / before present iteration

Greek

Δp	pressure drop