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Systematic Optimization Approach for Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™)

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A Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™) has been developed for rapid analyses of complex thermal cooling systems. The detailed heat exchanger design features included in this code (i.e. geometry, material properties, fuel/coolant properties, etc.) make *SRHEAT*™ a valuable tool in scramjet and hypersonic vehicle development, providing the low cost analytical capabilities that make possible the efficient development of aerospace components. A key feature of *SRHEAT*™ is its ability to optimize the heat exchanger thermal design for minimum fuel flow requirement while providing a structurally viable design. Optimization includes both the ordering of the cooling flow circuit and the sizing of the heat exchanger channels. Large computational times are required for standard optimization techniques due to the sheer number of interdependent variables associated with the complex thermal management system. Several methods have been developed and adapted to reduce computational time requirements of optimization. The result is a fast code with the built-in intelligence to make design decisions leading to an optimized thermal management system design.

I. Introduction

Managing the heat load to critical engine components remains a significant challenge in the design and operation of hydrocarbon or hydrogen fueled hypersonic vehicles. Passive and active methods can be used for heat-load management. One method for active cooling is to flow the fuel through critical areas of the engine structure using its heat sink capacity to provide the necessary cooling. In principle, the fuel can be used over a wide range of flight conditions if it has sufficient cooling capacity. After the fuel is heated within the engine structure, it is then burned in the combustor to produce propulsive thrust. For an efficient closed-loop system, the flow rate of fuel required for cooling should not exceed the flow rate necessary for propulsion. In practice, this becomes more difficult as the flight Mach number increases. It is possible that cooling of certain critical areas in the engine may elevate the flow rate requirement above that of the propulsion system, thereby resulting in the need to dump fuel overboard during certain parts of the mission, which dramatically reduces the efficiency of this type of air-breathing propulsion system and is a significant problem. *SPIRITECH*'s Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™) provides the heat exchanger designer with a user-friendly tool for optimizing the cooling system considering material selection, engine geometry, fuel/coolant selection, flight point cooling requirements, and heat exchanger geometry.

The Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™) is comprised of several modules

- **Thermal Module** calculates heat flux and temperature distribution within the heat exchanger panels.
- **Flow Module** calculates fluid boundary conditions within heat exchanger panels, and fluid property distribution through a cooling circuit, including frictional losses and heating effects.
- **Engine Performance Module** calculates hot gas boundary conditions for heat exchanger panels, and property distribution throughout the engine.
- **Structural Module** calculates the stresses in the heat exchanger panels.
- **Optimizer Module** optimizes the coolant circuit order, and the heat exchanger channel geometry.
- **Properties Module** stored library of material and fuel properties used within the thermal and flow modules respectively.

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These modules employ the input from a single source to evaluate the design of the user-defined heat exchanger. When directed by the user, the tool performs a system optimization, analyzing the heat exchanger performance over a range of design parameters.

This paper focuses on the Optimizer Module and the methods employed to speed convergence to an optimized thermal management system design. For further reading, Gamble et al.[12] describes the development of *SRHEAT*™.

II. Technical Discussion

A. Optimization Problem Definition

Optimization of the thermal system design is performed to minimize the fuel cooling flow requirement subject to the constraints that the propulsion system liner's maximum temperature is less than or equal to the material's maximum use temperature and the maximum fuel temperature is less than or equal to the fuel coking temperature. Also considered in the system optimization is the minimization of the cooling system weight, which can be separately evaluated (to be discussed later). The parameters for optimization include cooling circuit order and heat exchanger (HEX) channel geometry for each individual liner (Figure 1). For any given geometry and cooling circuit order, the mathematical system thermal model within *SRHEAT*™ is used to identify propulsion system liner temperatures and fuel coolant temperatures throughout the engine.

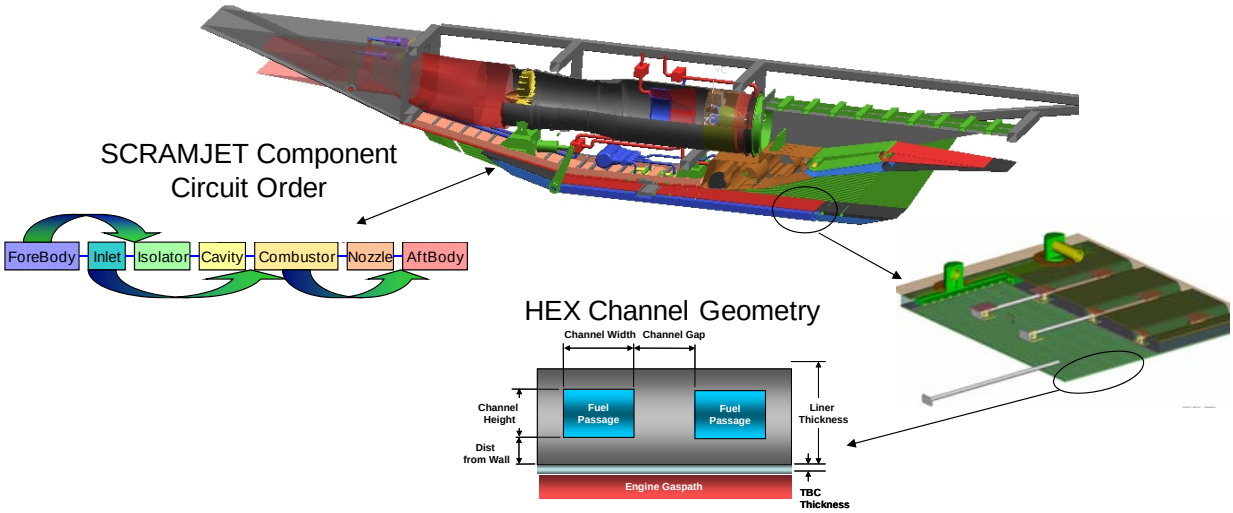


Figure 1: Cooling Circuit Order and Channel Geometry Optimization

Fuel flow is minimized when the system reaches its material and/or fuel temperature limits. The iterative logic diagram shown in Figure 2 was developed to minimize cooling flow by approaching these constraints. The principle behind the approach is that increasing the cooling flow results in both decreased propulsion system liner temperatures and decreased fuel temperatures. Therefore, as shown in the logic diagram, the maximum surface and fuel temperature from the "Thermals" solver is compared to the allowable limits, and the cooling fuel flow is adjusted until at least one of the limits is reached.

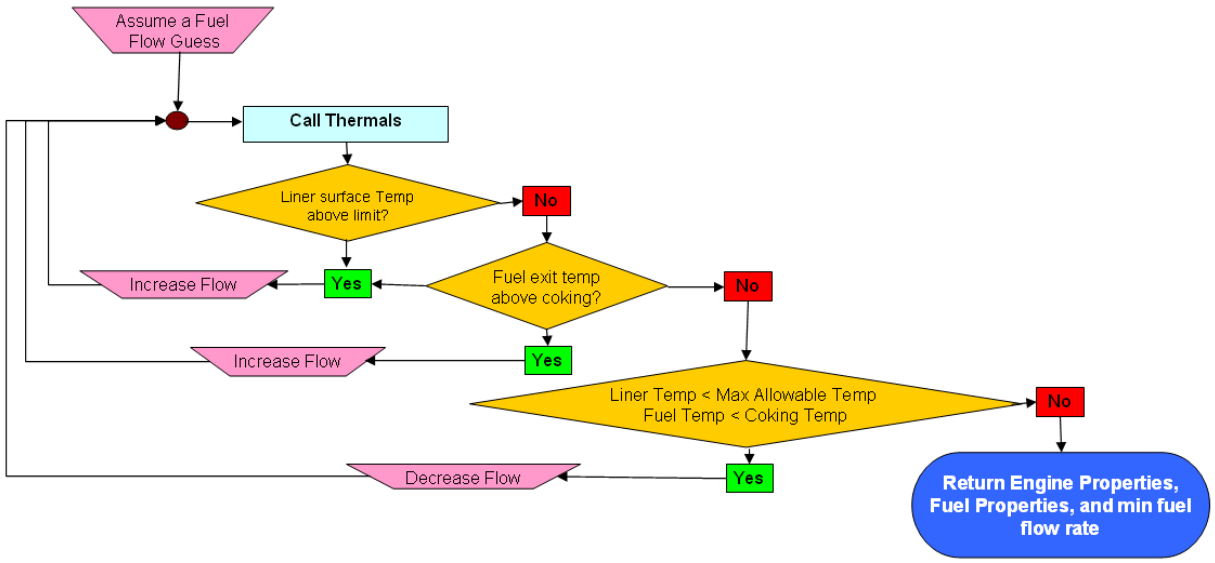


Figure 2: *SRHEAT*™ Minimum Cooling Flow Algorithm

To use standard optimization terminology, *SRHEAT*™'s minimum cooling flow algorithm is the system's *cost function* of the independent variables included in the system HEX channel geometry and the system circuit order. Since this particular cost function is not a continuous mathematical function for which the derivative can be found, the method chosen for optimization must minimize the cost function systematically in a guess and observe manner, through adjustment of the independent variables. Due to the fact that the system circuit order is a combinatorial optimization problem (the set of feasible solutions is discrete) while the HEX channel geometry is not, the common solution techniques available for optimization do not apply. Also, the solution techniques for a combinatorial problem are very different than those for a general problem. To enable a solution of this mixed class of problem, the *SRHEAT*™ cooling system optimization is broken into two parts – the cooling circuit order optimization and the HEX channel geometry optimization. The user has the ability to optimize circuit order, HEX channel geometry, or both simultaneously.

B. Circuit Order Optimization

1. Cooling Circuit Definition

Combinatorial optimization problems are inherently difficult due to the potentially large set of possible solutions which must be evaluated to find the global optimum. Even if all circuit elements were in series, for a system consisting of 19 elements, the number of possible combinations is on the order of 10^{17}. When branching of the cooling circuit is considered, the size of the solution set becomes essentially infinite. An infinite solution set cannot be solved over a finite time-span. Therefore, constraints were placed on the cooling circuit to reduce the solution set size. The circuit must have a single starting and a single ending point (fuel supply & fuel injector). To further reduce the solution set size, the branching structure of circuit elements is explicitly defined by the user using flow network "building blocks" (see Figure 3). This "building block" approach is based on templates containing parallel and series sub-circuits that are combined to create the overall circuit. Each branch within the "building block" sub-circuit is termed a "path", and may contain several elements. The templates were designed such that any possible circuit can be constructed with some combination of the templates. After the user has defined the building blocks within the cooling circuit, optimization is then based on the series ordering of the blocks and the circuit elements on each path within the blocks.

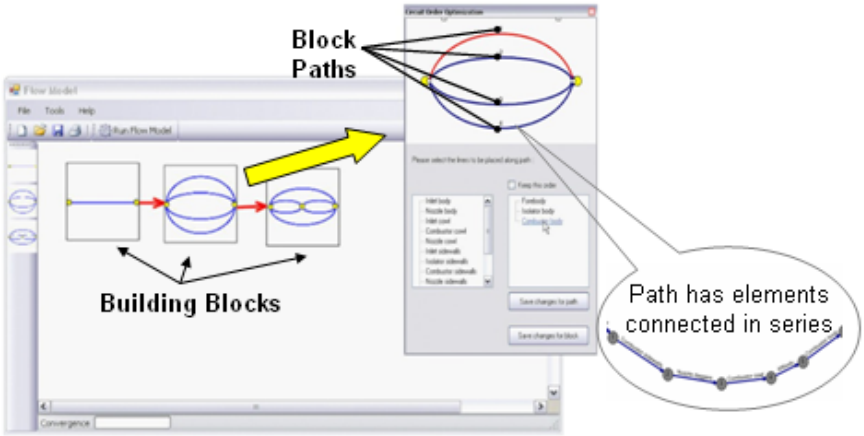


Figure 3: Example of Cooling Circuit Defined with "Building Blocks"

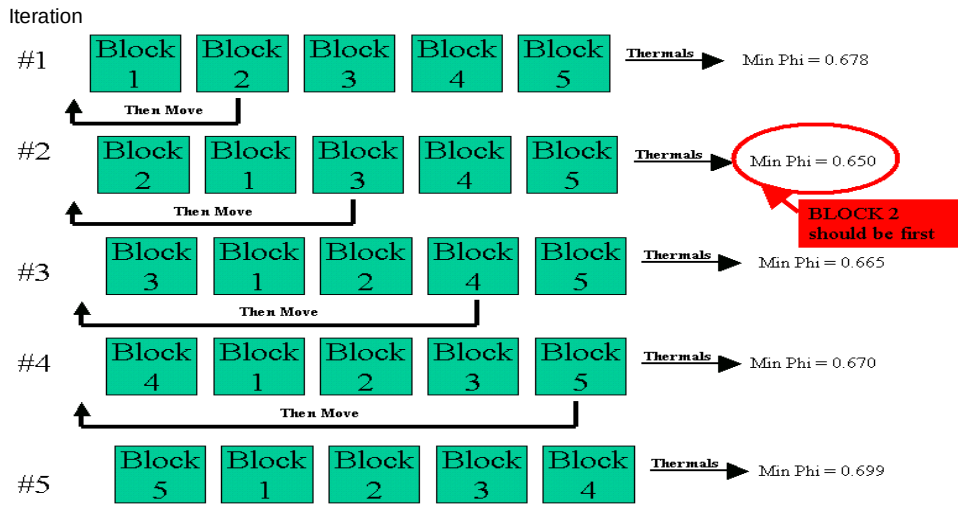
2. Systematic Optimization Method

The most effective approach for optimizing a combinatorial problem is to evaluate all members of the solution set. However, this is computationally costly, resulting in extremely long runtimes. The use of a heuristic approach derived from experience-based knowledge of system behavior allows a solution to be found through the evaluation of only a small portion of the total solution set, which is considerably faster than evaluating all possible solutions.

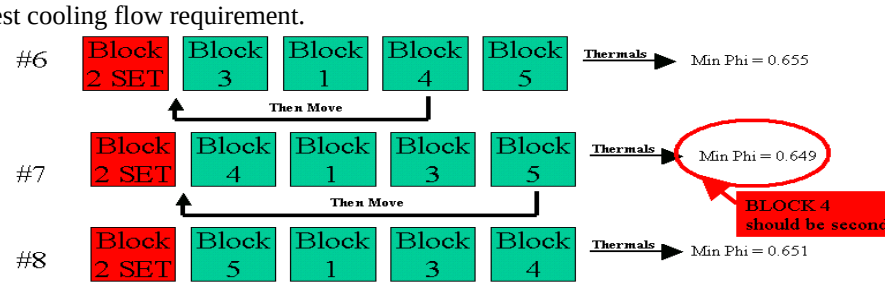
To build the experience base from which to define a heuristic method, the system behavior and sensitivity to the independent parameters was investigated through testing and observation. Correlation of the results was attempted against several relevant HEX parameters including the heat exchanger effectiveness ($\varepsilon = q/q_{max}$), the heat exchanger number of transfer units ($NTU = \dot{m} \cdot C_p/(U \cdot A)$), element fuel exit temperatures, and the liner heat loads. It was found that, due to the complexity and interdependencies of the system, direct correlation of the independent parameters cannot be used to describe the system's response to cooling circuit order variations. However, a clear and repeatable behavior was observed concerning system sensitivity to the element positioned first in the circuit order. This behavior is easily explained when considering that the fluid exit temperature from the first component represents the limiting temperature from which heat can be removed from the remainder of the circuit. This same trend follows with the second circuit element, the third, and so on throughout the circuit. Although a precise relationship between exit temperature and circuit order was not found, this behavior provides a general approach for improving the cooling circuit order within a heuristic procedure.

Based on the aforementioned observation, the heuristic solution procedure is simply a systematic ordering algorithm. By comparing circuits with only differing first elements, the proper first element can be identified, and the same process can be used progressively downstream through the cooling circuit.

Consider the following example for determining the optimum ordering of 5 of the aforementioned "building blocks". The iteration begins by assuming an arbitrary ordering of the blocks. In this case blocks are initially in numerical order from 1 to 5. The next 4 iterations follow by evaluating the system cooling flow requirements as each of the remaining 4 blocks is located first in the circuit, while leaving the other blocks in their same relative positions. For this example, iteration 2, with block 2 in the first position, provides the lowest cooling flow requirement, which means that block 2 should be located first.



Once the first block is determined, the next set of iterations proceeds with the number 2 "building block" in the first position. The remaining four blocks are sequentially evaluated as the second block in the circuit, while still maintaining the same relative ordering of the other blocks. In this example, iteration 7, with block 4 second, provides the lowest cooling flow requirement.



The iteration process is continued with block 4 in the second position. This procedure is repeated, sequentially determining the best block for each position until the overall order for minimum cooling flow requirement is determined.

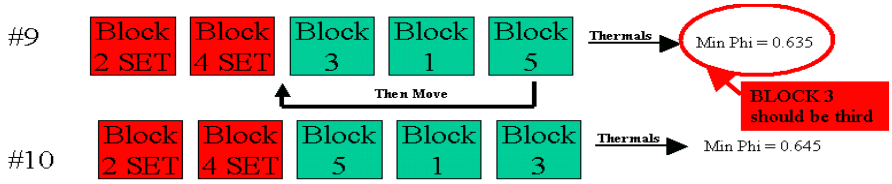


Figure 4: SRHEAT Systematic Circuit Order Evaluation Process

The paths within the "building blocks" from Figure 4 may also contain several circuit elements, but the optimum order of these elements can be achieved using the same systematic heuristic. It is important to realize that there is a degree of interaction between path ordering within a block and the order of the blocks themselves. To account for this interaction, the systematic approach described above is applied at the building block level and the block path level in an iterative sequence. It was observed that the block order generally has a greater effect on the flow requirement than does the path order. Therefore, within the iteration scheme, the order of the blocks is found first and then the order of all the series paths within each block is found. Once the new path order has been found, the previous block order is reevaluated, with the updated path order. If the block order changes from one iteration to the next, the process is repeated until the variation in cooling flow requirement is within the predetermined tolerance. Only the lowest flow is accepted during any level of the systematic heuristic, so the iteration is guaranteed to continue moving toward the optimum.

3. *Robustness Considerations*

Although the effects of the downstream block order tend to be small, they may become significant in some cases due to differing HEX channel geometry, HEX materials, and local engine gas-path conditions. Downstream order refers to the variations which result from the removal of a component to place it in a desired position. For example, in

Figure 4, as blocks are tested in the first position, the order of the last three blocks varies through 3-4-5, 2-4-5, 2-3-5, & 2-3-4, which will affect the circuit and could skew the ordering results. An example illustrating how significant this effect can become is shown in Figure 5, which shows results for every member of a 7 block solution set plotted as cooling flow requirement vs. the circuit order (sequential ordering of the integer block ID numbers, making a 7 digit number). The x-axis identifies the first block within the circuit orders. Close inspection of Figure 5 reveals that even if a set of circuit orders all contain the same first three elements, flow is still highly dependent on the remaining order.

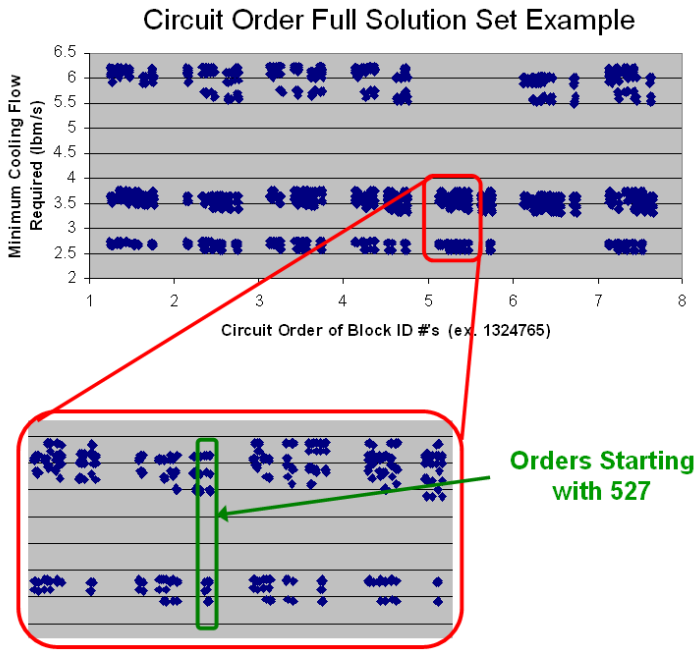


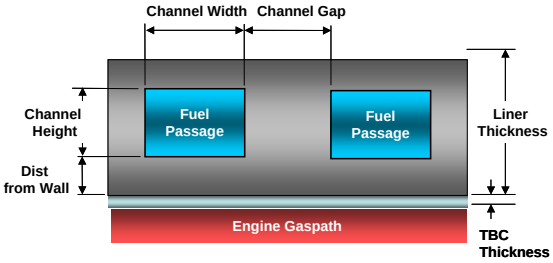
Figure 5: Cooling Flow Variations Due to Downstream Block Order

To ensure that these downstream effects are accounted for in the optimization, the systematic heuristic method must be repeated. Using the final solution from the first iteration as a starting guess, the second iteration starts with an initial guess which is closer to the optimum order. Since only the lowest cooling flow is accepted, iteration of the method is guaranteed to continue moving toward the optimum, resulting in a continuously improved ordering. Iteration continues until the reduction in minimum required cooling flow is less than the optimization convergence tolerance. In Addition, downstream order variations in the last few elements tend to be significant, as see in Figure 5, and are accounted for by evaluating all members of a solution set subgroup. Once the order of the first few elements has been determined, a relatively small number of solutions that contain the order of these first elements remain. The benefits of capturing a more definitive final optimum far surpass the cost of a few more iterations.

C. Channel Geometry Optimization

1. Cooling Optimization

The channel geometry optimization seeks to vary geometric parameters within user specified constraints to achieve the lowest cooling flow such that the maximum material temperatures and fuel temperatures are within the material and fuel coking limits. The HEX channel geometry consists of channel height, channel width, and gap between channels. Like the cooling circuit order, HEX geometry has a significant impact on the cooling flow requirement. Other parameters, such as liner thickness (to be discussed later), are optimized but are not contributors to the cooling flow requirement.



The HEX geometry dictates the thermal resistance to heat flow between the engine hot gas and the fuel coolant. Changes in channel geometry can affect fuel heat transfer coefficient by changing the local fuel velocity and can change the wetted surface area of the coolant, much like heat exchanger fins. Either of these changes affect the overall thermal resistance. An important concept to realize is that the optimum design in *SRHEAT*™ is not necessarily the design with the lowest possible thermal resistance. Although the lowest thermal resistance would result in the lowest surface temperatures, it would also cause the greatest coolant heat up and potentially violate the fuel coking constraint. Therefore a balance must be reached at the optimal HEX geometry to cool liners temperatures just below the limits yet minimize coolant heat up. This principle can be exploited during the search for the optimum as an indicator of the optimum geometry, where both the material limit and the fuel coking limit can be reached.

Several generalized mathematical optimization techniques exist for the solution of this type of problem. However, since each cooling circuit element (liner panel) may have different cooling channel geometry, the number of independent parameters (57) is too large to solve within a reasonable time span. The speed of the generalized mathematical techniques can be increased by exploiting observed system trends, or by simplifying the system to reduce the number of independent parameters.

Observation of system behavior indicates that minimizing the gap between the channels will reduce the cooling flow requirements regardless of the channel height or width. A plausible explanation for this behavior, which was reaffirmed using ANSYS, is that small channel gaps increase the overall wetted surface area (much like cooling fins), and allow for more channels to fit with a given width (reducing fuel heat up). Exploiting this behavior, the number of independent parameters may be reduced by always minimizing the channel gap.

Mathematical methods for optimizing the system cooling performance evaluate the cost function over the range of independent parameters, using an iterative approach to find its minimum value. Some generalized techniques, such as Newton's Method or the Conjugate Gradient Method, use the derivative of the cost function to speed the rate of convergence toward the optimum. However, this requires either that the derivative of the cost function is known or that it be accurately approximated using a linear assumption over small intervals. The derivative of the cost function for HEX optimization is not explicitly known, and the presence of multiple temperature constraints cause discontinuities which prevent linear approximations. Simple Descent is a robust optimization method that does not require knowledge of the derivatives, but lacks the convergence speed obtained when using derivatives.

The Simple Descent method is illustrated in Figure 6 for a hypothetical cost function of two independent parameters (y_1 & y_2). This figure shows that starting at an initial guess, y_1 is adjusted (holding y_2 constant) until the cost function is no longer decreasing. Similar changes are then made to y_2. Each variable is adjusted individually to guarantee cost decrease, alternating from one independent parameter to the next. The Simple Descent method proceeds by cycling through all of the independent parameters until the cost function is no longer decreasing. This method simplifies the implementation of upper and lower bound constraints on each HEX parameter since variables are adjusted individually. The speed issues associated with the method are addressed using simplifications to the analytical model and applying system trends, which will be discussed later.

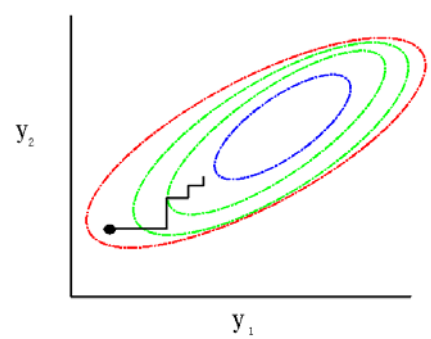
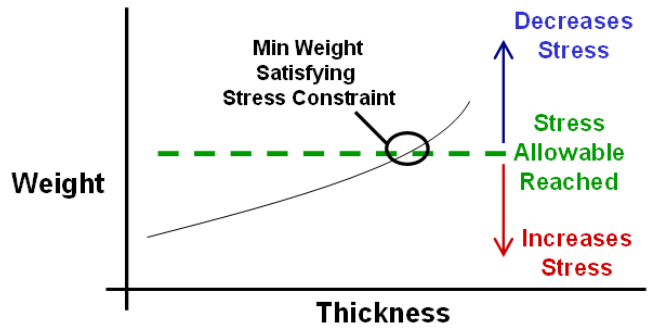


Figure 6: Simple Descent Method Illustration

2. Secondary Structural Optimization

In addition to the optimization of the channel geometric parameters that minimize the required cooling flow, *SRHEAT*™ also minimizes the liner panel weight while satisfying the constraint of acceptable maximum stress. The structural loads are the result of both fluid pressure differences and temperature gradients across a liner. The ability to withstand these loads is dependent on the attachment spacing, the channel wall thickness, and the overall thickness. Increases to the overall thickness and decreases to the attachment spacing result in reduction of the stress

due to the ΔP acting across the liner. Increases in the channel wall thickness result in a reduction of the stress induced by the fuel pressure. Since each of these structural optimization parameters have no effect on cooling flow, the structural optimization may be considered outside the minimum cooling flow algorithm discussed earlier. Using built-in stress calculations, *SRHEAT*™ solves for the maximum attachment spacing, the minimum channel wall thickness, and the minimum overall thickness required to provide an acceptable stress. By maximizing the attachment spacing and minimizing thickness, the weight is reduced to the bounding constraint of allowable stress. Since the complex thermal solution does not need to be recalculated as these parameters are varied, the structural calculations are fast, allowing a simple marching technique to be employed.



D. Simultaneous Optimization of HEX Geometry and Circuit Order

The goal of simultaneous optimization is to realize the globally best circuit order and HEX geometry combination. However, as mentioned earlier, the circuit order and HEX geometry cannot be simultaneously varied within a single solution technique. Also, HEX geometry and circuit order optimization are not independent, meaning that differing HEX geometries will result in a different optimum circuit order solution and vice-versa. The solution to this problem may be realized by assuming that, for any given circuit order, there exists a single optimum HEX geometry. Therefore, HEX geometry optimization must be encapsulated within the circuit order optimization method. Recall that the circuit order optimization method compares members of the solution set based on minimum cooling flow. The same is true during simultaneous optimization. However, in this situation the minimum flow represents the lowest which can be attained for any HEX geometry.

This nested optimization approach results in a runtime which is the product of the HEX geometry and circuit order optimization runtimes ($\text{time}_{\text{SimultOpt}} = \text{time}_{\text{HEXopt}} \cdot \text{time}_{\text{CircOpt}}$). Therefore, simplifications must be made to allow a solution to be found in a reasonable time. By allowing the code to run in different modes (Trade Study / Detailed Design), the user can specify whether a general initial assessment optimum is acceptable (Trade Study) or whether a high fidelity optimum solution is needed (Detail Design). A Trade Study analysis is generally completed within a couple of hours while a Detailed Design analysis could require overnight running.

The Simple Descent method was adapted to reduce computational time required for HEX geometry optimization. One clear simplifying assumption is to consider the case where all circuit elements are required to have identical geometric parameters. To illuminate system behavior, a matrix of parameters was evaluated using this assumption along with minimized channel gap.

Figure 7 shows the behavior of this simplified system based on data from every possible combination of height and width from 0.05” to 0.25” (channel gap is constant at the minimum manufacturing limit of 0.060”). The Surface in Figure 7 shows that several combinations of height and width have approximately the same flow requirements and occur in a minimum valley. Each of the height and width combinations within the minimum valley are possible optimum solutions since they all minimize the cost function. Note that the plateau, shown in yellow, is a truncation of data that continues to rise as high as 20 lbm/s. Also, note that the un-smooth waves in the surface are due to the convergence tolerance in *SRHEAT*™ to the surface and fuel temperature limits. Similar test cases with varied engine geometry, flight points, liner material, and cooling circuit orders were evaluated, and all showed the same surface shape with an analogous minimum valley. It is therefore assumed that this valley/surface shape is typical and may be exploited heuristically within a search technique.

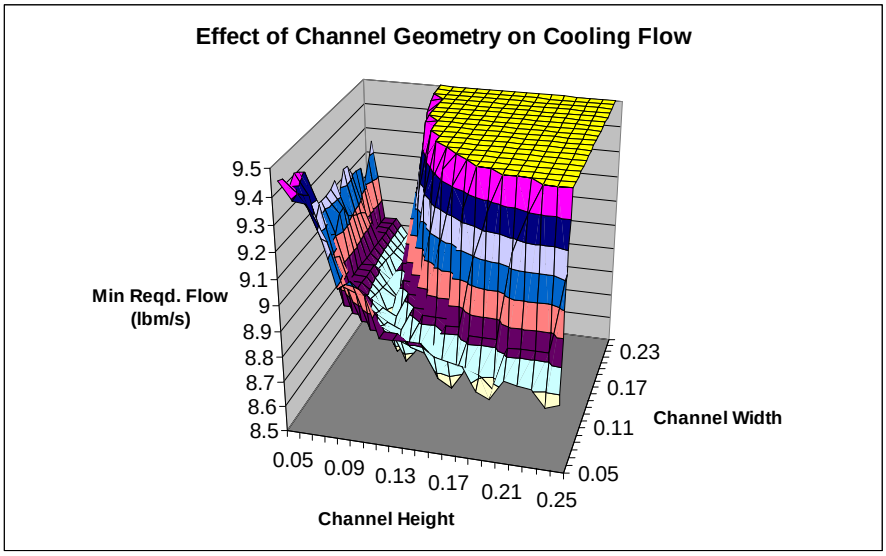


Figure 7: Case Study Matrix Results as all Elements H & W are identical

Recall that for any HEX geometry, either the fuel coking limit or the material maximum temperature limit must be reached at the minimum cooling flow. All designs in the valley of Figure 7 reached both limits simultaneously. An important note is that these limits are not necessarily reached on the same component, partially due to the varied engine core gas property distribution and fuel cracking (endothermic heat absorption over range of properties). To further illustrate the limit-reaching trend, Figure 8 shows the minimum cooling flow requirement for the specific case in which channel height and width are equal (aspect ratio is 1). Note that the trends in Figure 8 are typical for all aspect ratios.

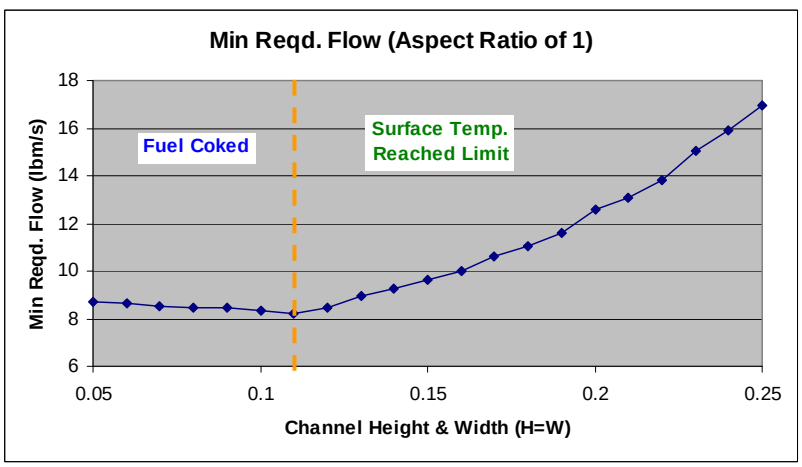


Figure 8: Limits Reached for Constant Aspect Ratio Channels

Since this behavior was confirmed for several test cases, it is reasonable to presume that the limit-reaching trend is also typical of any optimum HEX geometry. Therefore, the limit reached can serve heuristically as an indication of how both height and width should be modified to achieve the optimum design. For example, if the fuel coking limit is reached for a given HEX geometry, both the channel height and the channel width should be increased to reduce the fuel heat up, to increase the maximum surface temperature, and to reduce the minimum required cooling flow. The converse is true if the surface temperature limit is reached.

Although there may be no difference in cooling flow requirement for designs within the minimum valley, not all of these designs are equally feasible. The thermal stress provides a key differentiating parameter for selecting from these otherwise comparable designs. Figure 9 compares several height and width combinations from within the minimum valley using the thermal stress resulting from variations in thermal gradient. It shows a slight reduction in

thermal stress near an aspect ratio of 1. Upon further investigation for multiple configurations, it was determined that designs with an aspect ratio of 1, or as close to it as allowed by user-defined constraints, was found to provide the optimum HEX geometry.

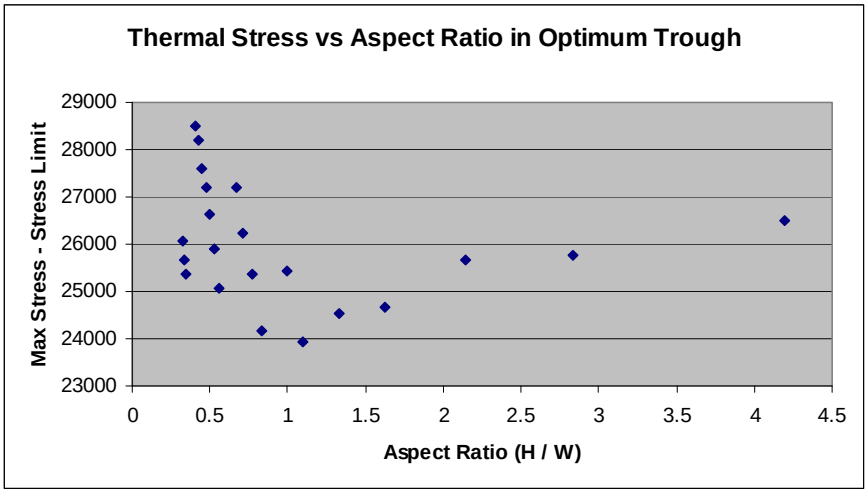


Figure 9: Thermal Stress Indicates Optimum Aspect Ratio

All of these heuristic trends were valid for a system in which HEX geometry was assumed identical among the cooling circuit elements. A similar study was attempted without that assumption, but no trends in system behavior were found. Using the simple descent method, the optimum HEX geometry for each cooling circuit element can still be found after a much larger set of evaluations, and requiring a much longer time. Therefore, *SRHEAT*™ uses the identical geometry assumption within Trade Study Mode to find a general optimum solution rapidly. In Detailed Design Mode the simple descent method is used to find the precise optimum.

III. Results/Discussion

A. Circuit Order Optimization

To validate the systematic heuristic, the optimum found must be compared to the complete solution set. If the optimum found is truly the global optimum, no member of the solution set will have a lower minimum cooling flow rate. For a thorough check of the method, this complete solution set comparison should be performed for different systems including: different flight points, different engine sizes, varied HEX geometry, varied materials, and different fuel types. Due to the lengthy evaluation time required to run every member of the solution set (~28 hours for 7 elements), the test cases included only one element on each block path. (Note that a test case was also evaluated containing multiple elements per block path, which confirmed the validity of the iteration scheme between block order and path order.)

Presented in Figure 10 are three validation cases each containing 7 blocks. Each of the three cases has a different combination of fuel type, liner materials, engine size, HEX geometry, and flight point. This variety in system parameters provides a broad validation of the method. Figure 10 shows the full solution set compared to the cases run during the systematic heuristic. Note that the x-axis of all three graphs represents groupings for which the numbered block (1 to 7) is in the first position of the sequence. This x-axis parameter allows for a grouping of cases with the same first component, within which there is a grouping of cases with the same second component and so on. The term “pass” in the graphs below refers to the iteration of the systematic ordering algorithm as the starting order is improved.

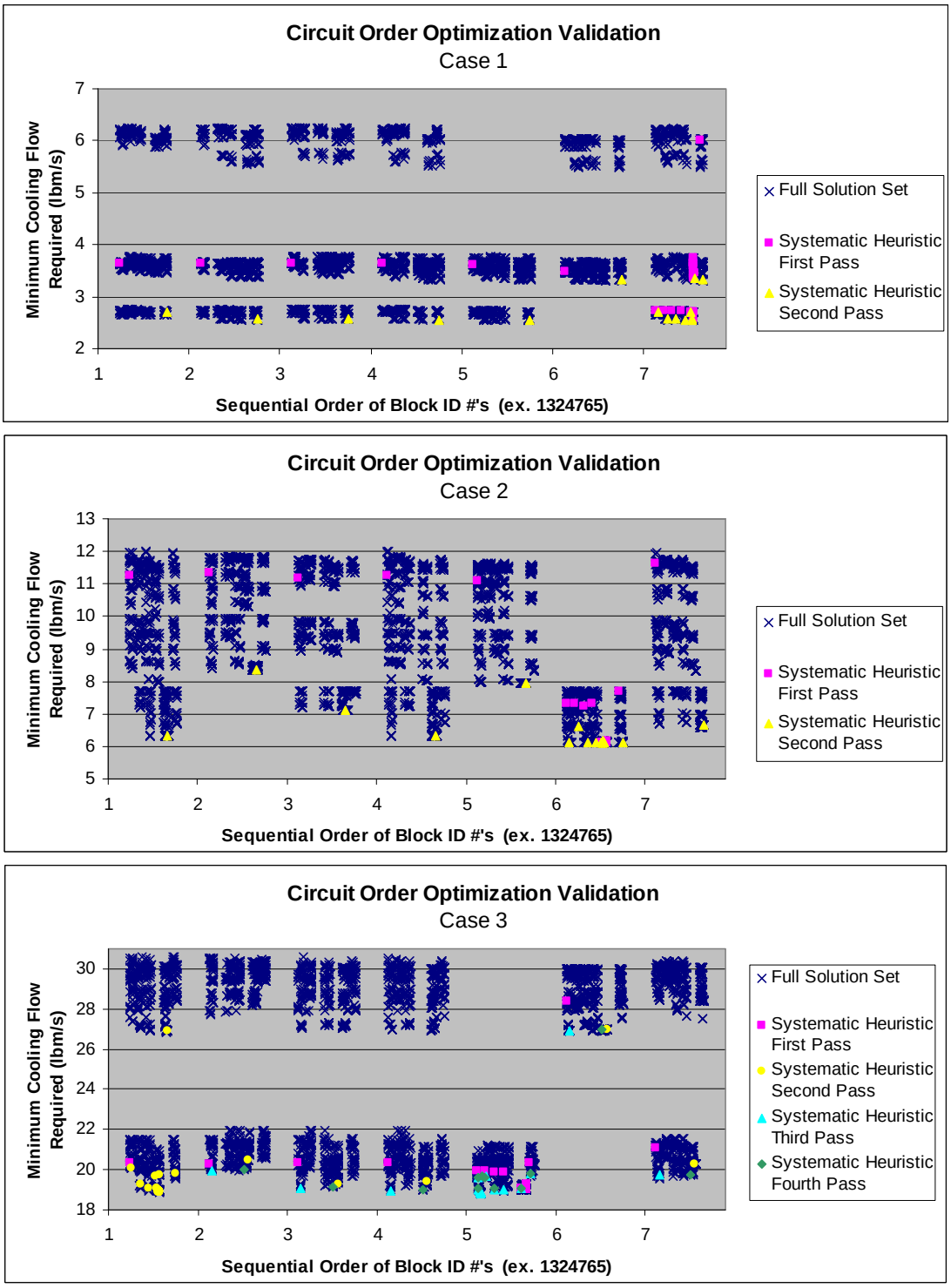


Figure 10: Circuit Order Validation Data

Figure 10 depicts how the systematic heuristic moves through the solution set during its search for the optimum. It is important to realize that the systematic heuristic has no awareness of the full solution set values shown in the graphs. Only the cases which are evaluated are used in the determination of the optimum circuit order. The first pass identifies the first component using the sequential downstream order, which oftentimes is already a reasonably good order (as for Case 3). Based on the first component selected, the method then continues to optimize the order

of the remaining components, finding the lower values within the component groupings seen in all of the graphs. The second pass or iteration of the method serves as a check to ensure that the sequential first order did not improperly skew the method toward a local minimum, and most of the time the second pass confirms that the order selected is best (as for Case 1 & 2). Case 3 illustrates that the second pass can result in a different ordering, which will eventually settle to the optimum.

Figure 10 also illustrates that several very different circuit orders have nearly the same cooling flow requirements. For these configurations, the optimum order can be selected based on other parameters, such as minimum plumbing weight required to route fuel between elements within the cooling circuit. Traditionally, the optimization of multi-goal objective functions is difficult problem, because the different goals are not globally optimum at the same point. One simple method to accommodate multiple objectives is to linearly sum the non-dimensional cost values of each goal and apply a constant weighting factor to determine the relative priority of each. In *SRHEAT*^{TM}, it is desirable that a cooling system has both the minimum required cooling flow and the minimum weight. Using the several near-optimum solutions obtained via the systematic heuristic and a user specified weighting factor (priority of flow vs. weight), the optimal cooling circuit is selected.

It should be realized that the only way to guarantee the global optimum of a combinatorial problem is to evaluate every single solution possibility. Therefore, it is possible that the systematic heuristic method used in circuit optimization will not find the absolute global optimum, because not every member of the solution set is evaluated. However, the nature of the method ensures that the optimized solution found will be within the specified tolerance of the global optimum. In this particular case the gargantuan number of possible combinations prohibits the evaluation of every possible solution. Table 1 highlights the scope of the full solution set for the simple case where all circuit elements are in series and shows just how efficient the systematic method is in reducing the number of iterations which must be performed to determine the optimized circuit.

Table 1: Combinatorial Solution Method Comparison

Number of Circuit Elements (n)	Full Solution Set	Systematic Heuristic		Percent of Total Solution Set (% Total Run Time)
	Number of Solutions Possible $n!$	Number of Solutions Run per iteration $24 + \sum_{j=0}^{n-4}(n-j)$	Conservative Estimate of Total number of Solutions Run (assume 3 iterations)	
7	5040	39	117	2.32 %
12	4.79E+08	84	252	5.26E-05 %
15	1.31E+12	123	369	2.82E-08 %
19	1.22E+17	189	567	4.66E-13 %

Note that the number of solutions evaluated corresponds directly to the time required for solution, and the percentage can also be viewed as a percent of total time required.

B. Channel Geometry Optimization

Both the simple descent method, and the limit-reaching heuristic were compared against the test matrices of height and width combinations covering full domain with a 0.01” grid. This comparison was made among several test cases, and validates the optimum solution techniques.

C. Simultaneous Optimization

The size of the solution set for simultaneous optimization is the product of the solution set for circuit order and HEX geometry, which is absurdly large. Not only would evaluating require several weeks of continuous computational operation, but the data set arrived at would be difficult to sort through. This brute force validation is not necessary, as it would only validate the assumption mentioned earlier, which requires a single optimum HEX geometry for any given circuit order. Recall that this single optimum was guaranteed when the secondary parameter of thermal stress was included in the HEX geometry optimization. Note that the individual validation of circuit and Hex optimization is retained when the each is used in conjunction.

IV. Conclusions

A key feature of *SRHEAT*™ is its ability to optimize the heat exchanger thermal design. Optimization parameters include both the ordering of the cooling flow circuit and the sizing of the propulsion system liner geometry. Methods employed have been developed and adapted with emphasis on runtime reduction. The result is a fast code with the built-in intelligence to make design decisions leading to an optimized thermal management system design.

Built into *SRHEAT*™ is a sophisticated thermal system optimization that accounts for numerous channel geometry parameters and countless possibilities for circuit ordering as well as multi-variable considerations, such as fuel temperature constraints, liner material temperature limits, system weight, and stress limits. Channel geometry optimization, while attainable through some generic techniques, consists of numerous design parameters and is further complicated when thermal, geometric, and structural constraints must be satisfied. The channel geometry optimization methods simplify the system in such a way as to reduce the design parameters which must be varied, isolate variation to individually satisfy constraints, and exploit general behavior to speed convergence. Circuit optimization is made possible through the development of a flow model "building block" approach, which allows the user to define the circuit through use of flow templates. The evaluation of a variety of near-optimum cases within the systematic method allow optimization of cooling circuits based on flow and plumbing weight associated with fuel routing. Despite the complexity of the system, the methods discussed provide an effective means of optimizing the thermal management system very quickly.

V. References

[1] E.J. Gamble, J.L Gutierrez, J. Bachmann, T. Jobin, D. Williford, *"A Scramjet/Ramjet Heat Exchanger Analysis Tool (SRHEAT™)"*, JANNAF, December 2005

[2] E.J. Gamble, J.L. Gutierrez, D. Giel, J. Bachmann, T. Jobin, D. Williford, C. Raffoul, "*Development of a Scramjet/Ramjet Heat Exchanger Analysis Tool (SRHEAT™)*", AIAA-2008-4614, July 2008