Proceedings of ASME Turbo Expo 2022
Turbomachinery Technical Conference and Exposition
GT2022
June 13-17, 2022, Rotterdam, The Netherlands

GT2022-82166

INTEGRATION OF SECONDARY AIRFLOW MODELING INTO SYNERGETIC CYCLE CALCULATION OF F CLASS INDUSTRIAL GAS TURBINE

Shanel Staple,
Gregory Vogel, Alex Torkaman
Power Systems Mfg., LLC
Jupiter, FL

Andrii Khandrymailov,
Viktor Yevlakhov
SoftInWay Switzerland GmbH
Zug, Switzerland

ABSTRACT

Industrial gas turbines are complex systems, and their proper analysis requires specific knowledge of the different components interacting with each other. One of the challenges is to accurately predict the overall performance of the system. To do so, a performance analysis tool can be used but it needs to rely on representative characteristics from the different elements. One of the key items required for the performance derivation is the understanding of the total cooling and leakage air (TCLA) and its distribution within the machine. A secondary air flow (SAF) tool is used to evaluate TCLA, but it needs to be "connected" with the overall performance model. The source locations of the SAF system are relatively straightforward to handle, but the sink (or dump) locations occurring in the turbine section require a detailed understanding of the pressure distribution within the flowpath. As a matter of fact, a change in SAF distribution to the turbine yields a change in turbine work output and load distribution that needs to be captured in the overall engine performance assessment. Furthermore, a change in turbine inlet boundary conditions also yields a change in pressure values for the SAF system. For these reasons, an accurate performance modeling of a gas turbine requires a so-called Synergy Loop to converge the overall boundary conditions of all its interacting modules and sub-models. This paper will describe the method used to integrate different commercial and in-house software to complete the Synergy Loop. The authors will also describe the different iteration steps possible between the specific components and the recommended iteration loop sequence for fast convergence.

Keywords: Gas Turbine, Secondary Air Flow, Secondary Air System, Gas Turbine Performance Modeling, Total Cooling Leakage Air

NOMENCLATURE

All nomenclatures used throughout this document can be found here. Please note that any nomenclature leading with a number can also be changed with another number as appropriate:

Aero	Aerodynamics
AOR	Analysis Of Record
BC	Boundary Condition
CIF	Compressor Inlet Flow
CFD	Computational Fluid Dynamics
CHT	Conjugate Heat Transfer
dP	Delta Total Pressure
GT	Gas Turbine
It.	Iteration
1V	1st Stage Vane
1B	1st Stage Blade
1SB	1st Stage Shroud Block
SAF	Secondary Air Flow
ID	Inner Diameter
OD	Outer Diameter
TCLA	Total Cooling and Leakage Air
Δp^*	Total Pressure Drop
ζ	Resistance Coefficient
ρ	Fluid Density
u	Fluid Velocity

1. INTRODUCTION

The Gas Turbine (GT) system has multiple sub-systems working together as one unit with the ultimate goal of exchanging chemical energy of the fuel into mechanical energy. While each subsystem has its own complexity and intricacies, the interaction and therefore dependency of each sub-system on the others creates an even more complex system of systems. This interdependency of individual components creates a challenge to analyze the GT as a synchronized unit. Another important consideration is the analytical time required to complete the analysis in a timely manner [1].

There are a few methods that can be used to model GT engines. These methods include:

1) Feedback Loop [1] – this method typically uses 1D or 2D tools that conduct calculations of entire sub-systems, which shares results via interfaces. The tools used for the sub-systems sacrifice fidelity for the sake of time, as there may be a need for multiple simulations for different design points.
2) Component Modeling [2] – this method goes a step further and has component models within the sub-system itself. In the case of SAF modeling, there are models for important sub-components such as orifices and labyrinths, which allows for more focused changes without interfering with the entire SAF system. It has a significant drawback when it comes to capturing tiny leakages between the important sub-components of the SAF system.
3) Computational Fluid Dynamics (CFD) [3][4] – this method uses either 2D or 3D CFD to model portions of the SAF system, or in some cases, the entire SAF system. This method is the best in terms of fidelity, but it comes at a cost of computation time and resources. Also, smaller gaps and leakages are problematic, and can lead to convergence issues and large mesh sizes.

To meet these challenges, an analytical loop known as the Synergy Loop has been utilized and will be the subject of this paper. This loop is a triangular iteration process that connects three key systems known as Modules: The Performance Module, which considers the overall performance of the engine (using the 0-D software known as NPSS), the Turbine Aero Module, which considers the turbine airfoil analysis of the engine (using the 2-D software known as SC90T), and the Secondary Air Flow (SAF) Module, which considers the entire SAF system (using the 1-D software known as AxSTREAM NET). There is also a sub-iteration process that takes place between the SAF and Combustor Modules (where the latter uses the 1-D flow solver software known as AFT). The Synergy Loop is similar to the Feedback Loop used in previous studies, but more engine systems are involved in the process. It adds more value in terms of giving a visual layout of the GT engine and how the different systems interact; something that isn't as clear in previous methods. As one runs iterations, it becomes easier to understand the entire process as well as the key parameters to monitor when converging on a design point. The goal of the Synergy loop is to establish common boundary conditions between all 3 modules as well as achieving convergence for important engine parameters. The focus of this paper is the SAF Module's role in the loop process and defining the ideal order of executing the modules in the loop. There will be a discussion about what the SAF Module requires as inputs, what it provides as outputs, as well as trends noticed in iterations. It has been observed that the Synergy Loop process has multiple approaches in terms of run order, but it eventually arrives at a converged result shared by an agreement between all 3 sub-systems in play. Each approach requires its own number of iterations, and the objective is to find the approach that uses the least number of iterations and encourages accurate bookkeeping.

2. MATERIALS AND METHODS

Multiple analytical modules are used to analyze various aspects of the gas turbine operation. It is important to discuss the different modules that take part in this analysis individually, before bringing them together in the overall analysis of the system which is referred to as the Synergy Loop.

2.1 Performance Analysis

A typical GT consists of four major components, which are shown schematically in FIGURE 1.

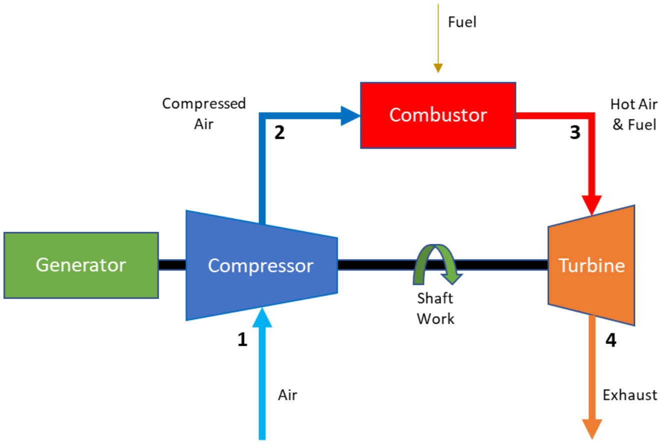

FIGURE 1: SCHEMATIC VIEW OF GT

The Compressor section supplies high pressure air to the combustor, where fuel is mixed with the incoming air and combustion takes place at near constant pressure. The resulting hot combustion product is directed towards a multi-stage axial turbine where mechanical work is extracted from the expanding gas. The mechanical work from the turbine is used to power the compressor and the generator. The underlying thermodynamic principles for the operation of a gas turbine is according to the Brayton Cycle, as shown on a TS diagram in FIGURE 2. The numbers in FIGURE 2 correlate with the numbers found in FIGURE 1. The 2s and 4s points in FIGURE 2 refer to the ideal Brayton Cycle, where the entropy remains constant. However, there is always some entropy gained in the non-ideal cycle, hence the dotted line modifications.

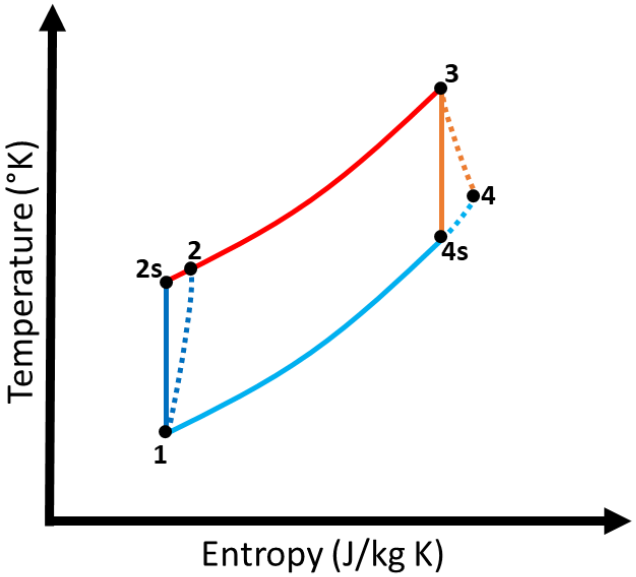

FIGURE 2: TS DIAGRAM FOR BRAYTON CYCLE

The overall cycle efficiency is a function of the ideal Brayton Cycle efficiency and the individual component efficiencies. The difference between the ideal and non-ideal cycle is driven by individual component losses. While compressor and combustor losses are significant contributors to the cycle loss, they are not discussed in detail in this paper since they are not significantly influenced by TCLA and SAF distribution. The main focus of this paper is on the turbine section losses, as that has strong ties to the other sub-systems. The major contributors to turbine losses are leakages and mixing losses associated with the secondary air flow injections. To accurately predict turbine efficiency, it is important to have the correct cooling and leakage flows as an input to the performance model. However, the cooling and leakage flows are driven by the flow path pressures which are a function of the turbine aerodynamics and stage pressure ratio in a multi-stage turbine. Turbine aerodynamics and efficiency are in turn influenced by cooling flow injections and associated mixing losses. It's evident that iteration would be required to synergize all the parameters involved in analyzing the GT performance.

The Performance tool used in this paper is a custom model based on NPSS software [5]. This model consists of all main components of the GT, and it utilizes relevant parameters from the turbine aerodynamics model to represent a non-ideal turbine for the purpose of this analysis (details of the Turbine Aero Module are described in the next section). It also utilizes bleed extraction information provided by the SAF model, which in turn provides boundary conditions at those bleed extraction points to the SAF model.

2.2 Turbine Aerodynamics Analysis

Various 1D, 2D and 3D methods can be utilized for the aerodynamic analysis of a multi-stage turbine. A viscous 3D multistage CFD model offers the best accuracy. However, the computational costs are too expensive for an iterative solution process. A 1D meanline code offers minimal computational cost, but in scenarios involving large GT airfoils, the accuracy of the aerodynamic analysis at a single section may not be accurate. A 2D streamline curvature analysis program known as SC90T [6] is used in the Synergy Loop for the best combination of computational efficiency and accuracy by using multiple sections for each airfoil. This software uses essential flow path and airfoil information such as inner and outer diameters (ID and OD), inlet and exit angles, pitch, chord and throat information to accurately model the aerodynamics of each stage. It is capable of calculating the flow conditions at the exit of choked airfoils along with the associated loss and outlet gas angle. It also has built-in correlation-based loss models to account for tip loss, trailing edge loss, and mixing losses associated with cooling flow injection [7]. FIGURE 3 below shows the schematics of a typical multi-stage SC90T model. Each line on a component in the figure represents a section of the airfoil with geometric information at those coordinates.

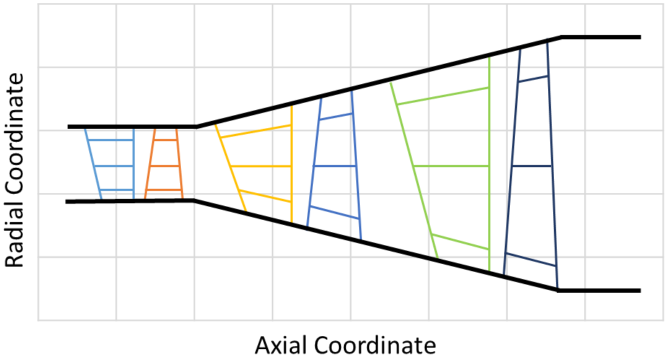

FIGURE 3: SCHEMATIC OF SC90T MODEL

Cooling flows can be injected at multiple locations as shown in FIGURE 4. However, shower head cooling flow injection is not possible and therefore the shower head cooling flow is split evenly between pressure side and suction side of the airfoil. While this is a limitation in the usage of SC90T, the impact is considered relatively small as the total stage cooling mass flow and associated mixing losses are still accounted for.

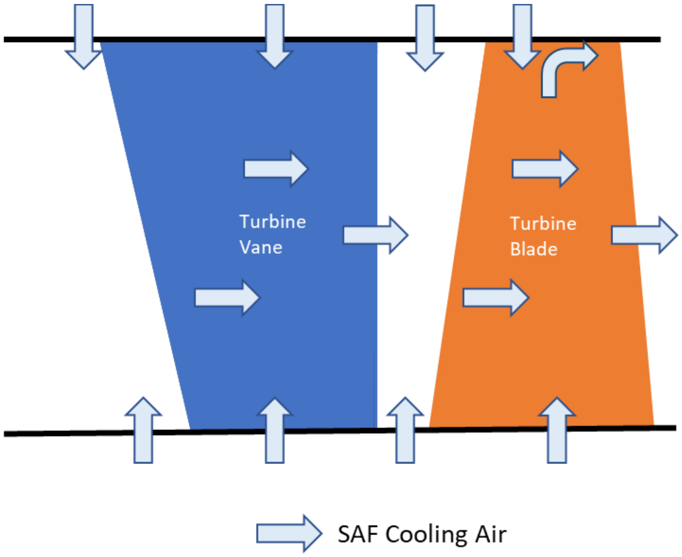

FIGURE 4: SCHEMATIC OF SC90T COOLING FLOW INJECTION

The boundary conditions (BC) for the aerodynamic model (which include turbine inlet conditions, turbine exit conditions, and TCLA) are provided from the initial starting point of the iteration. The output information from the aerodynamic model is in turn used in both performance and SAF models as essential input information.

2.3 Secondary Air Flow Analysis

The analysis of the SAF requires estimation of flow distribution and leakages through a cooling path. The secondary flow path usually includes complex rotor-rotor and rotor-stator cavities, different types of seals, orifices, deflectors, and other components and channels. Each element of the path has its own flow resistance and, as a consequence, influences pressure losses [8]. Due to the influence of rotating walls, the fluid flow inside the system is swirled. Thus, centrifugal forces occur and influence pressure distribution at different radial distances within the flow cavities. With potential heat exchange with surrounding walls, the fluid flow may be heated or cooled. Also, the fluid flow may be separated and mixed at different places in the system.

In order to model all these phenomena while performing SAF analysis, the thermal-fluid network approach was used. This approach is suitable to model complex thermal-fluid systems using different levels of abstraction (see, for example, [9, 10]). The main idea behind the approach is to model different sections of a fluid flow path and surrounding solid structure by representing them as one- and zero-dimensional components. They are able to connect with each other in order to form a thermal-fluid network and to simulate fluid and heat flow through these components (see FIGURE 5).

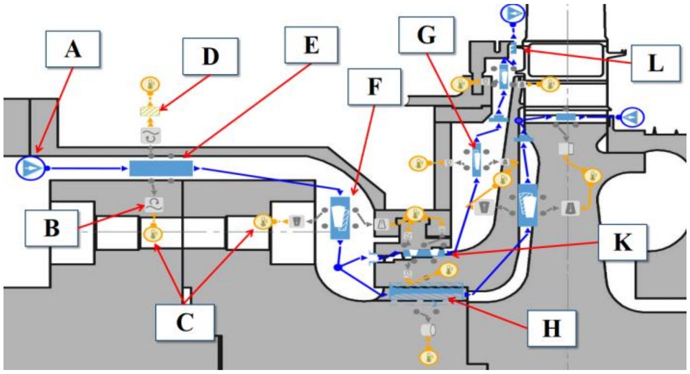

FIGURE 5: EXAMPLE OF THERMAL-FLUID NETWORK

(**A** - fluid flow boundary condition node; **B** - **s**urface element; **C** - thermal boundary nodes; **D** - solid material elements; **E** - fluid channel; **F** - centripetal radial cavity; **G** - centrifugal annular cavity; **H** - rotating inclined orifice; **K** - stepped seal; **L** - root seal)

Each component may be represented as a branch or a node, as shown in FIGURE 6. Branches describe different resistances to fluid and heat flow, while nodes connect branches and define boundary conditions.

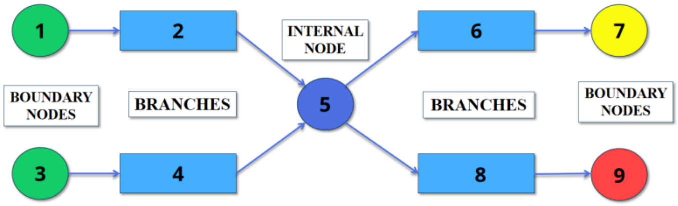

FIGURE 6: NODES AND BRANCHES

Depending on the required accuracy, the system can be modeled using different complexity levels. The considered fluid passages or solid structure section can be modeled using only one element or it is possible to discretize it using multiple sequentially connected elements.

Each component utilizes a set of equations, which may vary depending on the type of the component. The most common equations for components to model fluid flow (**E**, **F**, **G**, **H**, **K** and **L** in FIGURE 5) are the mass, momentum, and energy conservation equations. They are usually accomplished with an equation of state to relate fluid properties and the angular momentum conservation equation to model swirl. Mass and energy conservation equations deal with flow mixing and separation [11]. Momentum equation usually takes into account resistance of the component to fluid flow based on the empirical resistance coefficient. This coefficient can be derived using equation (1)

$$\Delta p^* = \zeta \cdot \frac{\rho \cdot u^2}{2} \tag{1}$$

where Δp^* – fluid flow total pressure drop between inlet and outlet of a branch component; ζ – resistance coefficient;

ρ – fluid flow density; u – fluid flow velocity. Also, the momentum equation may take into account the presence of mass forces, which captures the influence of centrifugal force and gravity on fluid flow.

The components to model heat flow between fluid flow and the surrounding walls (**B** in FIGURE 5) usually contain different correlations to calculate heat transfer coefficient depending on fluid flow and solid wall properties. Similarly, the components to model heat flow through a solid structure (**D** in FIGURE 5) contain correlations to calculate heat transfer coefficient for a solid material and also energy conservation equations.

All mentioned equations form several systems. These systems are solved using Newton-Raphson method sequentially in iterations while all systems are converged with a given tolerance. As a result of calculation, the solver computes fluid flow properties (such as pressures, densities, velocities) and heat flow properties (such as heat fluxes and temperatures) for all thermal-fluid network components.

The SAF model requires input data that fall into two categories. The first category is boundary conditions (**A** in FIGURE 5), which includes inlet and outlet boundary conditions for both the compressor and turbine sections. These parameters can take the form of total or static pressures and temperatures, and permit mixing of the two as well. The second category is geometric data, and this is represented by channels and cavities cross sections, length, areas, etc. Both forms of input are mandatory for successful simulation.

2.4 Combustor Flow Analysis

The combustor model participates in the Synergy Loop as a sub-iteration with the SAF Module, since it has a direct influence on the SAF system. The model used in the iterative process is designed using Applied Flow Technology (AFT). AFT is a 1-D fluid network solver which utilizes different flow elements such as pipes, bends, fans, heat exchangers, junctions, pressure source/sinks and flow source/sinks. FIGURE 7 shows an example of a combustor model as well as its link to an actual GT combustor via key locations. The combustor model represents the flow from the exit of the compressor (**A**) to the entrance of the turbine (**C**), while considering the intricate flow areas of the combustor, the additional fuel injected, as well as the extracted flows to feed the 1st Stage Vane (**B**). It is a pressure driven model that must match the expected mass flow after considering the Compressor Inlet Flow (CIF) and bleed extractions, with the pressure drop across the combustor being a fallout parameter.

2.5 Synergy Loop

The Synergy Loop is the iterative process that involves all the beforementioned components. As stated in the introduction, the GT system is a complex system of systems, and each sub-system has to be in balance with other sub systems for the entire system to function properly. The diagram in FIGURE 8 is an accurate representation of all the contributors to the process, all the required inputs/outputs, as well as all the sub-iterations and information exchange outside of the synergy loop. Each module has unique information that it provides to the other modules in the iteration process.

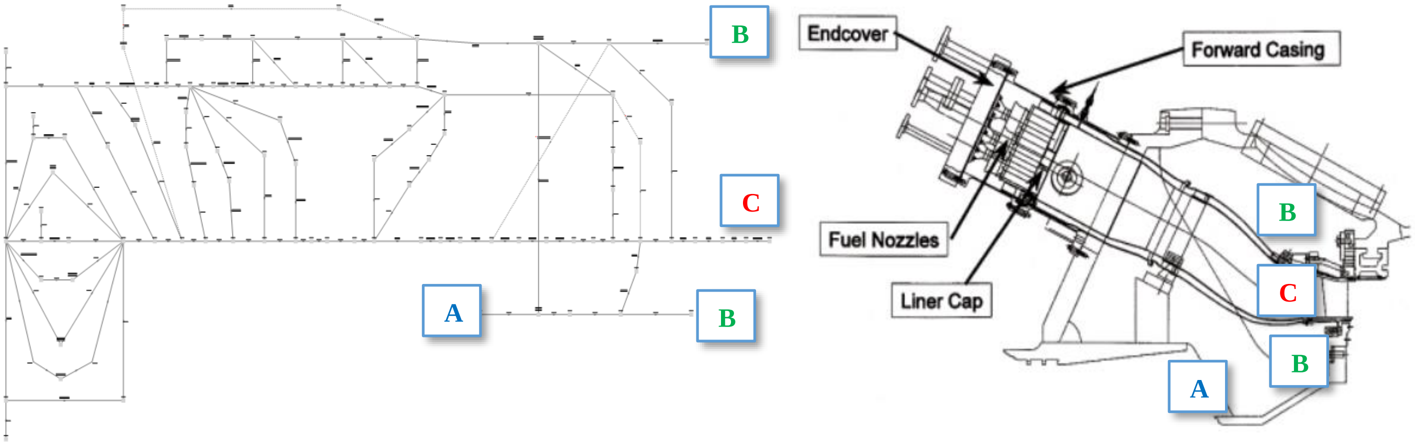

FIGURE 7: COMBUSTOR MODEL AND REPRESENTATIVE CONNECTIONS IN A COMBUSTOR [12]

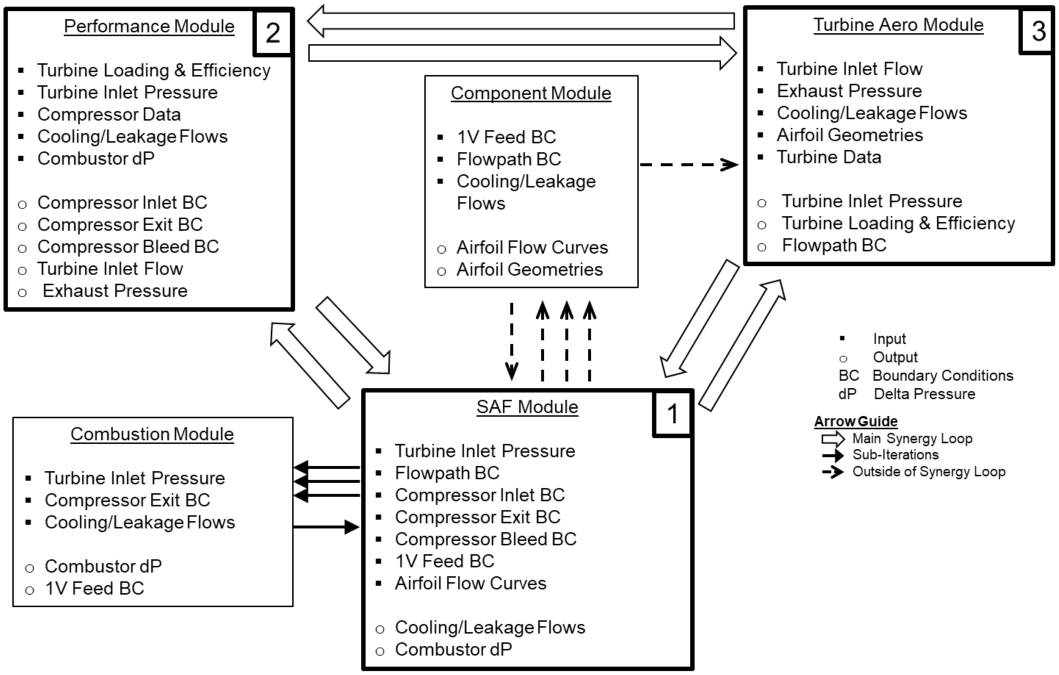

FIGURE 8: SYNERGY LOOP DIAGRAM

The loop can be initiated by any of the 3 main modules, but it is normally initiated by the SAF Module for a couple of reasons:

1) The SAF Module tends to require the most time in regard to convergence
2) The SAF Module has the most interactions outside of the loop, in the form of sub-iterations and communication with the Component Analysis Module upon Synergy Loop convergence

Depending on the information available, the SAF Module can initiate the loop in two different ways:

1) Using current outputs from both the Performance and Turbine Aero Modules – this is the easiest form of initiation, and is the preferred option if the modules have already been established
2) Using new outputs from either Performance or Turbine Aero Modules, and manually updating remaining boundary conditions in the SAF model – this option is usually required if the Synergy Loop is based on a new engine where models do not currently exist. The manual inputs are usually based on some form of engine data, or the best estimate available

The SAF Module also has a sub-iteration which must take place with the Combustor Module, and the interaction between the two takes place at the 1st Stage Vane (1V) feed (see **B** in FIGURE 7). With the Combustor model requiring a mass flow output to the 1V, it is imperative that the SAF model has an equivalent mass flow level. The 1V tends to consume the most air from a SAF standpoint, so that makes synergizing the interaction even more critical.

The main output information from the SAF Module is the mass flow values of all dedicated cooling air, purge air, and leakages. This information is presented in the form of a %CIF to allow for easy ratio comparisons with changing CIF. The Combustor Delta Total Pressure (dP) is also passed along from the Combustor Module, as the Performance Module uses that parameter in order to conduct energy balance calculations for the entire GT engine. The output information is presented to the Performance and Turbine Aero Modules simultaneously.

The Performance Module is next in the loop, using the latest available information from the SAF and Turbine Aero Modules. It conducts its analysis and provides an output file to both SAF and Turbine Aero Modules, which will be used in the subsequent SAF iteration. The Performance Module provides all upstream BCs, related to the bleeds and main air extraction points.

The Turbine Aero Module is the final step in the first iteration loop, providing information to the other modules as appropriate. The Turbine Aero Module provides all downstream BCs, which are based on the expected pressure and temperature profile in the flowpath between the exit of the combustor upstream and the entrance to the exhaust cylinder downstream.

The cycle then returns to the SAF Module, where the iteration process begins once again. There are multiple arrangements that can define an iteration, but this current order works well for bookkeeping purposes. The comparison of this current iteration loop order and another will be explored in the next section, as the time factor is also very important [1].

Each iteration is bookkept and compared to previous iterations, checking if the convergence criteria has been met. For SAF, the convergence criterion is the following:

$$\Delta\%CIF \leq Criteria \qquad (2)$$

The parameter $\Delta\%CIF$ is the difference in total cooling flow between the current iteration and the previous. Expressed in terms of %CIF, it is a good metric to observe in regard to convergence behavior. When the criterion is met, the current SAF result becomes the Analysis Of Record (AOR): in other words, the converged solution. However, it isn't the official AOR until the additional criteria are met:

1) All other modules have small convergence errors as well, granting them AOR status
2) SAF is run one last time as a test using the AOR results from the other modules, still generating a Δ%CIF that meets the threshold. This result is deleted, as it is only a check.

Once the above criteria are met, all AOR results become the official converged solution of the Synergy Loop.

With a converged solution, the information is passed on to the Component Module, where the turbine component models are updated with the information. The Component Module is not a part of the Synergy Loop; therefore, the required parameters are not provided to the module until the loop achieves convergence. The input parameters to the Component Module will help generate the appropriate BCs for more complex Conjugate Heat Transfer (CHT) analysis as well as conducting case studies on the individual turbine components. The parameters are also used as a cross-check to verify that component mass flows and engine conditions are similar to those components represented in the SAF model.

The Synergy Loop is a process that can be used for any class of GT engine. Matter of fact, it is a method that can be used for any iteration process that has multiple modules with shared boundaries; so long as the interface between the modules are defined.

3. RESULTS AND DISCUSSION

Besides the importance of generating accurate results, the amount of time required to generate accurate results is also of equal importance. Multiple Synergy Loops have been run in recent times, using two primary iteration loop orders. The expectation is that convergence will be achieved regardless of run order, but there could be a difference in the number of required iteration steps, which ultimately determines the time required to achieve convergence.

3.1 Loop Order #1

Loop Order #1 involves a mini loop between the SAF and Turbine Aero Modules to convergence before updating the Performance Module. See designated sequence of events below.

1) SAF Module runs
2) Performance Module runs
3) Turbine Aero Module runs
4) SAF and Turbine Aero Modules run until convergence
5) Repeat Steps 2 through 4 until convergence met for all modules

From a physics standpoint, this loop order makes the most sense, hence the initial approach. The iteration results are provided in TABLE 1 and TABLE 2 below, where the %CIF are presented as scalars with respect to the converged total TCLA value.

	It. #1	It. #2	It. #3	It. #4	It. #5
1V	52.858	52.787	55.484	55.528	55.282
1B	13.536	13.519	13.540	13.542	13.489
1SB	3.725	3.720	3.718	3.719	3.704
2V	14.500	14.483	14.471	14.470	14.418
2B	6.586	6.578	6.610	6.610	6.586
3V	5.635	5.628	5.612	5.612	5.592
3B	1.339	1.338	1.565	1.564	1.558
Total TCLA	98.179	98.053	101.000	101.044	100.629

TABLE 1: LOOP ORDER #1 SAF MODULE TCLA RESULTS

	It. #6	It. #7	It. #8	It. #9
1V	54.586	54.590	54.771	54.719
1B	13.460	13.460	13.473	13.468
1SB	3.699	3.698	3.706	3.703
2V	14.417	14.416	14.448	14.443
2B	6.586	6.586	6.596	6.593
3V	5.599	5.599	5.608	5.605
3B	1.471	1.471	1.470	1.468
Total TCLA	99.816	99.821	100.072	100.000

TABLE 2: LOOP ORDER #1 SAF MODULE TCLA RESULTS(continued)

To observe the convergence behavior of the entire loop, it's important to see how each parameter is changing between iterations, which is given by the $\Delta\%CIF$ term. FIGURE 9 shows how the $\Delta\%CIF$ changes with each iteration.

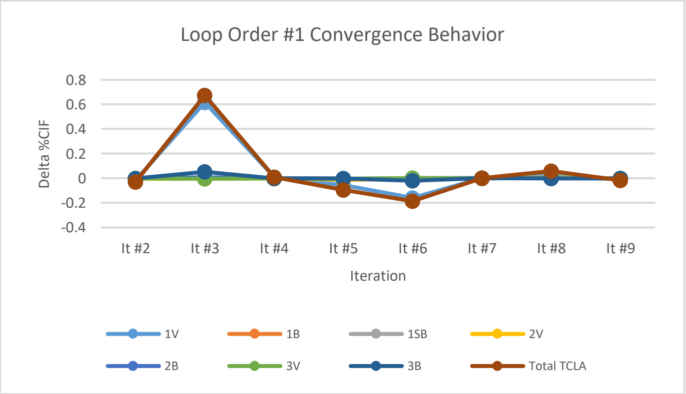

FIGURE 9: CONVERGENCE BEHAVIOR OF LOOP ORDER #1

Iterations 3, 6, 8, and 9 are the iterations that included updated values from the Performance Module after convergence between the SAF and Turbine Aero Modules. The sudden divergence at those iteration points was expected due to the exclusion of the Performance Module during the mini-iteration process. However, note that as the loop progresses, the diverging spikes decrease in amplitude, which indicates that convergence is in progress. Iteration 9 didn't experience any divergence at all, since all required thresholds had been met for all modules. The 1V was the slowest to converge with the most significant diverging spikes, hence why both the 1V and Total TCLA lines are almost perfectly aligned throughout the iteration process.

Between the first and last iterations, there is a 2% change in total TCLA. It may appear small, but it is actually significant considering potential CIF values for industrial GT engines. For example, for a hypothetical CIF value of 1000 pounds per second, a 2% difference in TCLA equates to a difference of 20 pounds per second of air. SAF air consumption is considered expensive air, so it is imperative to only extract what is needed to properly cool and purge the system without too much of a power output penalty. Along with the TCLA of the SAF system, there are other parameters to converge as well. The mixed polytropic efficiency of the turbine is also monitored via the Turbine Aero Module. The convergence behavior of the polytropic efficiency for Loop Order #1 is shown in FIGURE 10 below.

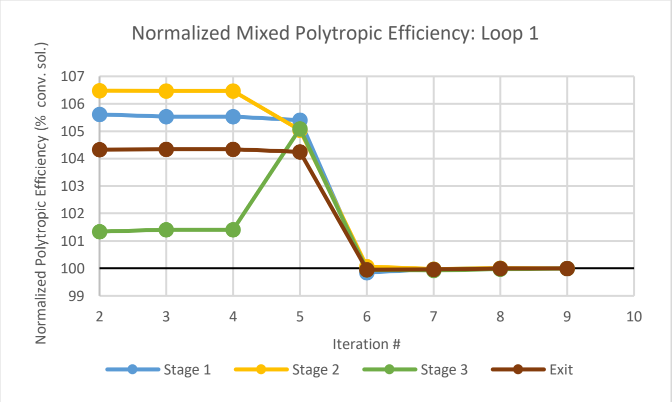

FIGURE 10: NORMALIZED MIXED POLYTROPIC EFFICIENCY OF LOOP ORDER #1

It is noted that some efficiencies are up to 6.5% higher than the converged value between the 2nd and 9th iterations, which indicates that a single iteration isn't enough to consider the loop converged. With the objective of the Synergy Loop being to have shared boundary conditions as well as non-significant changes of multiple engine parameters, it is important to continue the process until all parameters meet the criteria of convergence.

3.2 Loop Order #2

Loop Order #2 took a slightly different approach. Instead of mini-iterations between SAF and Turbine Aero Modules, the same run order is maintained throughout the entire loop process, seen below.

1) SAF Module runs
2) Performance Module runs
3) Turbine Aero Module runs
4) Repeat Steps 1 through 3 until convergence is met for all modules

This Loop Order has one major advantage compared to the previous: It is a simpler process. The simplicity makes it a lot easier to bookkeep, which helps in two different ways: 1) It is easier to resume an ongoing loop after a pause, and 2) It is easier to track input and output files when an error is generated during iteration. These advantages alone may make this loop order the preferred option, but it is still important to check the convergence speed. TABLE 3 shows the results of a Synergy Loop completed using this loop order, again presented as scalars with respect to the converged total TCLA value.

	It. #1	It. #2	It. #3	It. #4
1V	54.451	53.813	53.710	53.445
1B	15.869	15.964	15.943	15.864
1SB	4.152	4.160	4.156	4.146
2V	9.997	10.049	12.223	12.224
2B	6.233	6.326	6.322	6.310
3V	6.219	6.235	6.231	6.213
3B	1.569	1.706	1.723	1.798
Total TCLA	98.490	98.253	100.309	100.000

TABLE 3: LOOP ORDER #2 SAF MODULE TCLA RESULTS

Similar to Loop Order #1, it's important to observe how the $\Delta\%CIF$ is changing between iterations. The convergence behavior of Loop Order #2 can be seen in FIGURE 11 below.

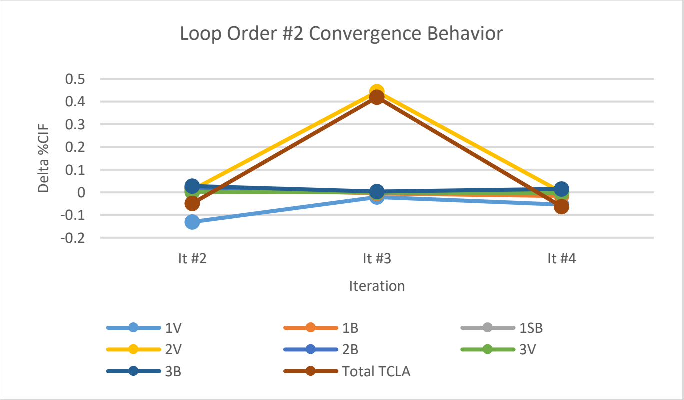

FIGURE 11: CONVERGENCE BEHAVIOR OF LOOP ORDER #2

FIGURE 12 shows the change in mixed polytropic efficiency with Loop Order #2.

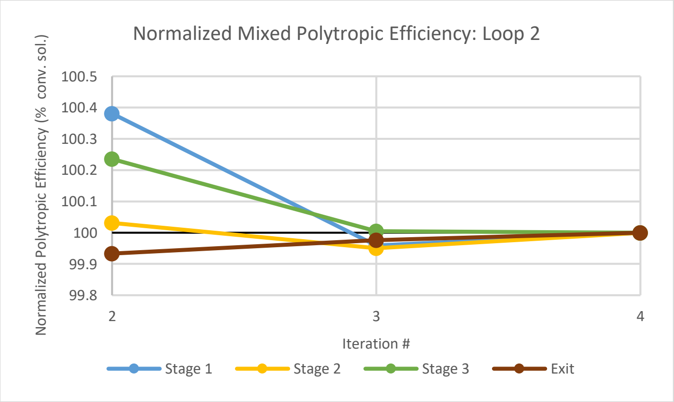

FIGURE 12: NORMALIZED MIXED POLYTROPIC EFFICIENCY OF LOOP ORDER #2

In FIGURE 11, the 2V experienced a divergence at Iteration #3 due to a change that had to be made to the SAF model geometry. Geometric changes are discouraged during synergy loops because they prolong the iteration process in a similar manner as module exclusion. However, there are times when changes are required, and beyond extending the process, they usually do not alter convergence. On the other hand, FIGURE 12 shows that the mixed polytropic efficiency has excellent converging behavior at Iteration #3, which further emphasizes the need to continue iterations until all critical engine parameters are changing by insignificant amounts set by their criteria. Also note that the normalized mixed polytropic efficiency of Loop Order #2 is at a much smaller magnitude. This is due to the inclusion of the Performance Module in all iterations, unlike Loop Order #1. All other parameters converged quickly as well, and even the divergence experienced during Iteration #3 in FIGURE 11 met the convergence criteria by Iteration #4. A test was done using Iteration 4's results, and the testing results were also within the acceptable range of convergence.

3.3 Discussion

FIGURE 9 and FIGURE 11 clearly indicate the difference between the two methods in regard to required number of iterations for convergence, which in turn affects the time required to complete a Synergy Loop. Each module has a different time requirement, as seen in TABLE 4.

Module	**Normalized Time Required**
SAF Module Iteration	0.083
Performance Module Iteration	0.01
Turbine Aero Module Iteration	0.083
Synergy Loop 1 Total	**1.594**
Synergy Loop 2 Total	**0.708**
CFD (micro-turbine) [13]	**1**

TABLE 4: RUN TIME PER ITERATION AND TOTAL ITERATION TIMES

Loop Order #2 is the faster loop of the two that were explored. As seen in TABLE 4, the total run time of the Synergy Loop is reduced by more than 50%. The lesson learned is that any level of exclusion or geometric modification during the Synergy Loop will prolong the process. Even though Loop Order #1 may make sense from a physics standpoint, excluding the Performance Module adds in additional iterations as well as additional diverging spikes each time. Triggering diverging spikes is not recommended, as it could adversely affect convergence. Fortunately, the Synergy Loop is robust in regard to convergence, so it simply lengthens the process. Including all modules throughout the entire process not only reduces the occurrence of diverging spikes, but also reduces the number of iterations required to run a Synergy Loop, resulting in a reduced convergence time seen in TABLE 4. Add in the other advantages of better bookkeeping for recording and troubleshooting purposes, and it becomes quite evident that Loop Order #2 is the best choice. It should also be added that any variation of that loop order is also applicable, so long as all 3 modules are run once during each iteration and no geometric changes are made.

But how does the Synergy Loop compare to other iteration methods? Compared to the iteration time of a micro-turbine CFD model of 19 million cells, the total run time is represented with a normalized time value of 1 [13]. With an industrial turbine, model sizes can be significantly larger if the entire SAF system is included, so the convergence time used for normalization is on the lower end compared to standard CFD models of gas turbines. Loop Order #1 has a larger run time vs. the CFD run, but Loop Order #2 is 29.2% less than the micro-turbine CFD comparison.

It is also crucial to tie these efforts back to engine data. Before conducting the Synergy Loop, static pressure measurements from engine data are used to initialize the boundary conditions at the beginning of the iteration. The goal is not to mimic the boundary conditions exactly, but instead to match the normalized pressure profile per stage, with the turbine inlet pressure being the base pressure (normalized value of 1). This will ensure that the converged model will have a similar profile that is independent of the turbine inlet pressure value. The comparison of the normalized pressure profile between the converged Synergy Loop and engine data is provided in FIGURE 13 below.

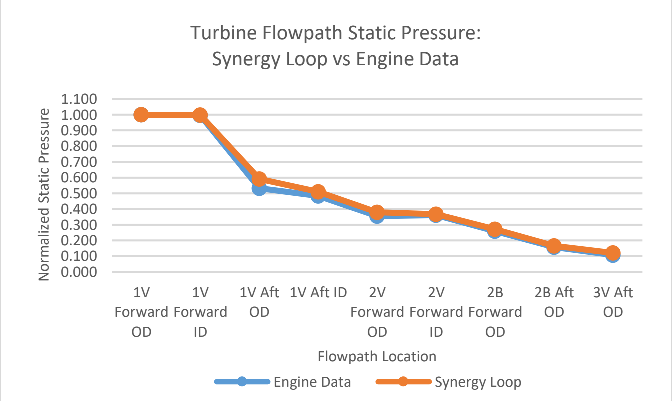

FIGURE 13: TURBINE FLOWPATH PRESSURE COMPARISON TO ENGINE DATA

The largest deviation from the engine data was for the 1V Aft OD measurement, with a normalized pressure difference of 0.06. Otherwise, the converged Synergy Loop has even smaller deviations from the engine data in other locations.

4. CONCLUSION

The Synergy Loop is a very useful iterative process that creates a design point for engine operations. The process is very robust in terms of convergence and tends to arrive at synergy regardless of execution order. The results have also been validated by engine data due to the small deviations in normalized flowpath pressures between the two. However, each loop order requires its unique number of iterations, which affects the time required to achieve convergence. After discussing the modules and the roles they play in the iteration process, it was necessary to investigate multiple loop execution orders and observe the number of iterations required to achieve convergence. Upon comparison of two unique loop orders, it was found that Loop Order #2 required the least amount of iteration steps to achieve convergence. It was also observed that this particular loop order was easier to execute as well as bookkeep, which made it an even more favorable option. The key is to include all modules in each iteration and to limit geometric changes as much as possible.

As developed as the Synergy Loop is, there is always room for evolution and growth. There are many aspects of the loop that have a lot of user interaction involved, which in itself can cause errors and increase convergence time. There will be future endeavors to automate a lot of these steps to reduce iteration time even further, which may open the window for other enhancements, such as optimization or design space exploration. Until then, the current Synergy Loop will continue to be a great contribution to modeling GT engines at accurate design points.

ACKNOWLEDGEMENTS

The authors would like to thank Power Systems Mfg. and SoftInWay for sponsoring this research and permitting its publication. We would also like to acknowledge contributions from Gregory (Brenton) Shirley, Shi-Ming Li, Michele Borja, Elena Pizano, and Kuo-Ting Hsia.

REFERENCES

[1] Peoc'h, Timothé *Integration of Secondary Air System for Multidisciplinary Design Optimization of Gas Turbines*, 2020.

[2] Alexiou, A., Mathioudakis, K., *Secondary Air System Component Modeling for Engine Performance Simulations*, Journal of Engineering for Gas Turbines and Power, May 2009

[3] Reed, John A., Afjeh, Abdollah A., *Computational Simulation of Gas Turbines: Part 1 – Foundations of Component Based Models*, International Gas Turbine & Aeroengine Congress & Exhibition, September 30, 1999

[4] Reynolds, W.C., Alonso, J.J, Fatica, M., Aircraft Gas Engine Turbine Simulations, 16th AIAA Computational Fluid Dynamics Conference, June 2003

[5] Naiman, Cynthia *Numerical Performance System Simulation*. 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit on Numerical Propulsion System Simulation (NPSS), July 6, 2006

[6] Came, P M *Streamline Curvature Throughflow Analysis of Axial Flow Turbines*, Proc. First European Turbomachinery Conference, VDI Berichte 1185, p.291, 1995

[7] Ito, S. Eckert, E. Goldstein, R. *Aerodynamic Loss in a Gas Turbine Stage with Film Cooling*, Trans ASME vol.102, p.964, October 1980.

[8] Idelchik, I. E. *Handbook of Hydraulic Resistance*, Begell House, New York (2008).

[9] https://www.softinway.com/software-applications/1d-system-simulation/

[10] Yevlakhov, Viktor, Moroz, Leonid, Khandrymailov, Andrii, and Hyrka, Yurii. *Transient Analysis of Aircraft Oil Supply System with Fuel-Oil Heat Exchangers during Abrupt Change in Engine Operating Mode*. Proceedings of ASME Turbo Expo 2021. GT2021-59992. June 7, 2021.

[11] Khandrymailov, Andrii, Moroz, Leonid, Yevlakhov, Viktor, Staple, Shanel and Vogel, Gregory. *An Approach to Model a Lossless Junction for Fluid Network Calculations in Turbomachinery*. Proceedings of ASME Turbo Expo 2020. GT2020-16079. September 23, 2020.

[12] Davis, L. B., Black, S. H., *Dry Low NOx Combustion Systems for GE Heavy-Duty Gas Turbines*, GE Power Systems, Schenectady, New York, October 2000

[13] Teixeira, Mateus, *Fully Coupled Fluid Dynamics Engine Simulation of a Gas Turbine*, November 29, 2018