AIAA-2010-6642

Thermal Management and Fuel System Model for TBCC Dynamic Simulation

Eric J. Gamble* and Dan Haid†
SPIRITECH Advanced Products, Inc, Tequesta, Florida

A dynamic simulator is being developed to demonstrate all modes of supersonic operation, including mode transition, for a Turbine-Based Combined Cycle (TBCC) propulsion system. The High Mach Transient Engine Cycle Code (HiTECC) is a highly integrated simulation tool comprised of models for each of the TBCC systems whose performance and controllability affect the thrust and operability of the propulsion system. The reported work details the development of the Thermal Management and Fuel System model conducted in the second year of a multiyear effort to develop a dynamic TBCC simulator. Once completed, this model will significantly extend the state-of-the-art for all TBCC modes of operation by providing a numerical simulation of the systems, interactions, and transient responses affecting the ability of the propulsion system to transition from turbine-based to ramjet/scramjet-based propulsion.

I. Nomenclature

A	area
c_p	specific heat
c_d	discharge coefficient
D	diameter
f	flow friction coefficient
FN	Flow Number
h	heat transfer coefficient
k	head loss coefficient; conductivity
L	length
m	mass flow
M	mass
p	pressure
q	energy flow
t	time
T	temperature
v	velocity
V	volume or Displacement
x	distance
ε	wall roughness height
η	efficiency
μ	viscosity
ρ	density
T	Torque
ω	rotational speed

Subscripts

A	compressible flow node
B	compressible flow node
C	compressible flow node
f	fuel flow path
g	gas path
H	hydraulic value
m	metal
ref	reference node
S	rotational mechanical node
$sonic$	evaluated at sonic condition
$tank$	evaluated at tank condition
th	thermal
vol	volumetric

II. Introduction

THE need for the National Aeronautics and Space Administration (NASA) Aeronautics Research Mission Directorate (ARMD) Hypersonic Project is based on the fact that all access to earth or planetary orbit and all entry into earth's atmosphere or any heavenly body with an atmosphere from orbit (or super orbital velocities) require flight through the hypersonic regime. The hypersonic flight regime often proves to be the design driver for most of the vehicle's systems, subsystems, and components. If the United States wishes to continue to advance its capabilities for space access, entry, and high-speed flight within any atmosphere, improved

* Vice President, SPIRITECH Advanced Products, Inc., member AIAA
† Aerodynamic Engineer, SPIRITECH Advanced Products, Inc., member AIAA

understanding of the hypersonic flight regime and development of improved technologies to withstand and/or take advantage of this environment are required.

A critical element of NASA's hypersonics research is the development of combined cycle propulsion systems, including rocket-based combined cycles (RBCC) and turbine-based combined cycles (TBCC). Based on the Next Generation Launch Technology (NGLT), TBCC, Two-Stage-to-Orbit (TSTO), National AeroSpace Plane (NASP), and High Speed Propulsion Assessment (HiSPA) studies, a turbofan and ramjet variable cycle engine is best suited to satisfy the access-to-space mission requirements by maximizing thrust-to-weight ratio while minimizing frontal area and maintaining high performance and operability over a wide operating range. The TBCC Dynamic Simulation Model Development Program discussed in this paper advances the technology readiness level of TBCC systems by developing the simulation and controls software to model all modes of operation over its mission, including mode transition from gas turbine to dual-mode scramjet propulsion, a requirement before controlled wind tunnel testing or flight testing can be accomplished through this region of operation. Within this program, modeling tools are being developed from fundamental physics and are being integrated into a comprehensive dynamic simulation tool to determine the transient performance, providing actual event durations to properly configure the propulsion system control logic. Work accomplished to date includes the development of the Propulsion System[1], the Hydraulic and Kinematic System[2], and the Thermal Management and Fuel System discussed here.

III. Technical Discussion

A. System Summary

The Thermal Management and Fuel System simulates fuel flow, fluid energy, and thermal energy transfer for both the low-speed and high-speed flow paths. This model couples a transient flow model with a transient thermal model for determining the dynamic response of the fuel and gas path flows and corresponding hardware for the propulsion system. A one-dimensional compressible flow solver allows a variety of fuels, including hydrogen, to be modeled.

This system is organized similarly to the other systems modeled in HiTECC, as shown in Figure 1. The system is broken up into three sub-systems: Flow, Power, and Storage. The Flow sub-system models the fluid and energy flow through gas path panels, valves, and other plumbing components. The Power sub-system models the flow of power to and from the battery, motor, and fuel pump components. The Storage sub-system models fuel flow to and from the storage tank and its associated plumbing components.

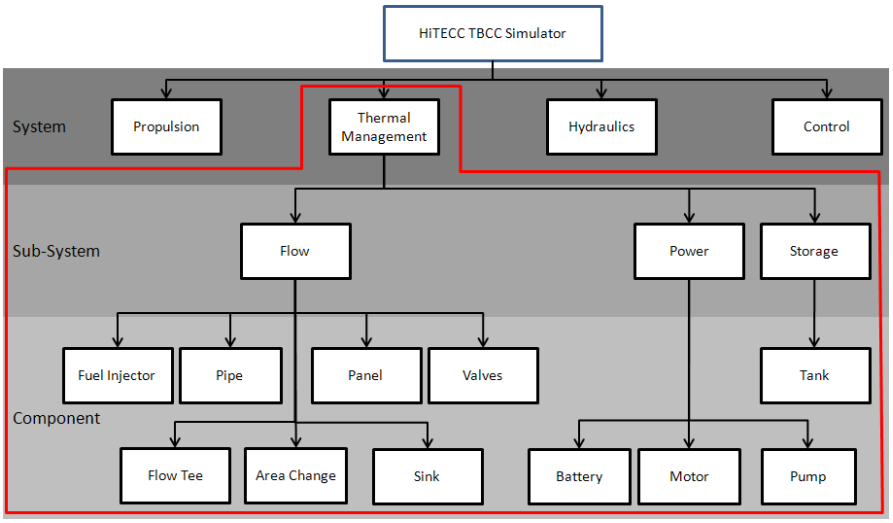

Figure 1. HiTECC TBCC Simulator Organization.

B. System Design

1. Environment

The Thermal Management and Fuel System is modeled in the Simscape™ environment. This environment was selected for a number of reasons. Other simulator systems use Simscape™ and/or Simulink™, and by keeping a common environment, interfaces can be made to be simple and computationally efficient. Also, a common solver selected from Simulink™'s list of proven solvers can be used to reduce risk. Finally, the Graphical User Interface is common among systems and familiar to the user, allowing the user to understand the interfaces between systems, sub-systems, and components and to make changes to them as needed.

The Thermal Management and Fuel System requires physical models in the electric, mechanical, thermal, and compressible flow domains. Simscape™ includes libraries for the electric, mechanical and thermal domains. It does not include compressible flow in its foundation library. A custom compressible flow library was built during this task to meet this requirement.

2. Compressible Flow Model

Although the domain and components are custom, the compressible flow model is built around the same physical network approach used in the existing libraries, as illustrated in Figure 2. Unique to the compressible flow model is the use of two sets of "across" and "through" variables. The "across" variables are the pressure, p, and temperature, T, consistent with other sub-systems and components in interfacing domains. The two "through' variables are mass flow, m, and energy, q. The selection of these variables ensures the balance of the mass and energy equations throughout the system. The momentum equation and state conditions must also be balanced in a compressible flow model. The momentum equation is balanced inside of each component in the form of relations between the "through" and "across" variables. Calculations are based on flow in the direction of node A to node B, with A often being referred to as the inlet and B, the outlet. However, components are capable of handling flow in either direction. Finally, a look-up table is used to determine the density, ρ, at each node from the pressure and temperature. This allows for a wide variety of fuels to be modeled without the use of sophisticated state models that would be computationally intensive. These look-up tables also provide specific heat at constant pressure, c_p, viscosity, μ, and sonic speed, v_{sonic}, of the fluid when required.

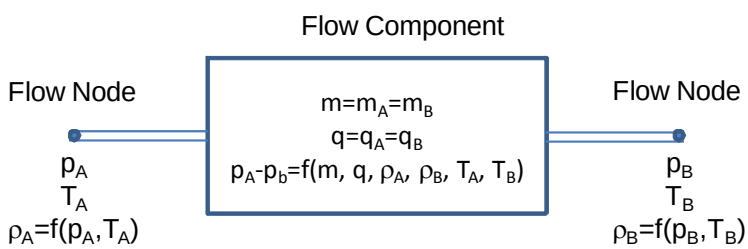

Figure 2. Compressible Flow Model Physical Network

Ease-of-use was a high priority during the development of the components and subsystems of the Thermal Management and Fuel System. This led developers to focus on minimizing inputs required from the user, allowing the user to set units for each input individually, and eliminating double inputs. By eliminating double inputs, not only is the number of inputs reduced, but the robustness and accuracy is increased by reducing the likelihood of inconsistencies between components. One result of this initiative was having a component's inlet area in the flow model be linked to the upstream component's exit area.

3. Fuel/Coolant and Material Properties

The Thermal Management and Fuel System uses lookup tables for fuel/coolant properties and has the ability to use material tables as a potential future capability. The data for these lookup tables has been incorporated into MATLAB™ workspace matrices, readable by Simscape™. Fuel/coolant properties have been generated using NIST SUPERTRAPP[3] for the following fuels: Jet-A, H2, JP-7, JP-8, JP-10, and RP-1. Material thermal properties were generated from the MMPDS Handbook[4], and the Aerospace Structural Metals Handbook[5] for the following: Haynes® 282, Inco 625, Inconel® 718, Haynes® 188, Waspaloy®, Hastelloy® -X, and Haynes® 230. The property look-up tables require absolute pressure and temperature. Therefore, the reference pressure, p_{ref}, and temperature, T_{ref}, are required to be zero.

4. Compressible Flow Model Verification

A prototype compressible flow model was built to facilitate understanding and minimizing the risk associated with this task. The HiTECC compressible flow model was verified by comparing its results against one-dimensional compressible flow theory. Two cases were run. The first was viscous flow through a constant area duct, and the second was inviscid flow through a constant area duct with heat addition. The fluid modeled was air. The results for the viscous flow case are plotted on the h-s diagrams shown in Figure 3. The Fanno line predicted by the model for the viscous flow case was within one percent of the one-dimensional compressible flow theory predictions up to the sonic point. Likely sources for the differences include the use of a variable specific heat for the HiTECC compressible flow model and numerical tolerances.

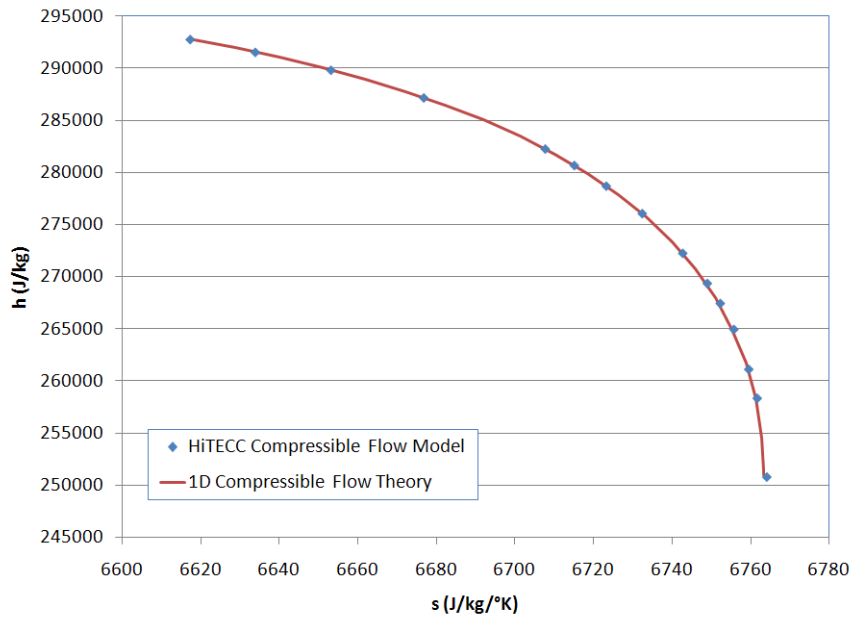

Figure 3. Compressible Flow Model Verification – Viscous Flow

The results for the heat addition case are plotted on the h-s diagrams shown in Figure 4. The HiTECC compressible flow model was run with both constant and variable specific heats. The HiTECC model results with constant specific heat matched within one percent of one-dimensional compressible flow theory up to the sonic point. The results with variable specific heat showed a shift to the left and down, as would be expected with the increase in specific heat with temperature.

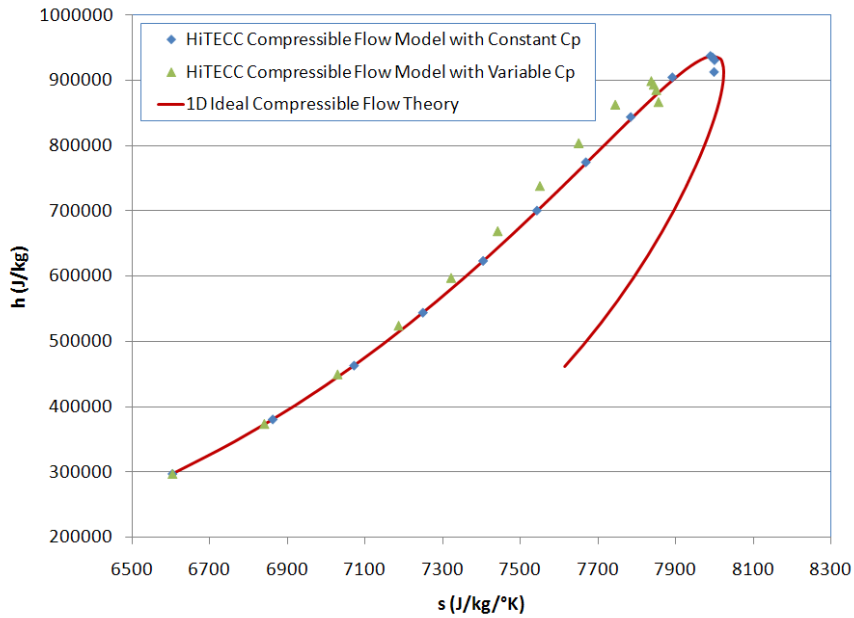

Figure 4. Compressible Flow Model Verification – Heat Addition

C. Component Descriptions

Component features defined during the software design process are summarized in Table 1. Column descriptions are as follows: *Inputs* refer to data required from the user, *Outputs* are data that will be provided to the user during a simulation, and *Interfaces* are data shared with adjacent components. Details on the modeling calculations and user interface for the individual components are contained in the following sections of the report.

Table 1. Thermal Management and Fuel System Component Summary

Component	Inputs	Outputs	Interfaces	Model
Fuel Storage Tank	Initial Volume, Initial Temperature	Remaining Volume	p, T, m, q	Compressible Flow
Pipe	Dimensions Loss Factor Network Location	None	p, T, m, q	Compressible Flow
Valve (Orifice)	Dimensions Discharge Coefficient Network Location	None	p, T, m, q	Compressible Flow
Fuel Injector	Dimensions Flow Number Network Location	None	p, T, m, q	Compressible Flow
Flow Sink	Flow Area Network Location	None	p (unchoked) m (choked)	Compressible Flow
Flow Tee	Flow Areas Network Location	None	p, T, m, q	Compressible Flow
Area Change	Flow Areas Network Location	None	p, T, m, q	Compressible Flow
Panel	Dimensions Material Properties Network Location	Panel Temperature	p, T, m, q	Compressible Flow Simscape™ Thermal
Pump	Performance Table	None	Speed, Torque, p, T, m, q	Compressible Flow Simscape™ Mechanical
Motor	Performance Table	Speed, Torque	Speed, Torque, Current, Voltage	Simscape™ Electric
Battery	Initial Energy	Remaining Energy	Current, Voltage	Simscape™ Electric

1. Fuel-Storage Tank

The Fuel-Storage Tank is an unsteady model of a constant pressure tank that balances the mass, m, and energy, q, entering and exiting by varying the tank fluid volume, V_{tank}, and temperature, T_{tank}. The user inputs the inlet and exit areas, A_A and A_B, initial volume, V_{tank}, initial total temperature, T_{tank} and the fixed total pressure, p_{tank}. The Tank is governed by Equations 1 through 6.

$$p_A = p_{\tan k} \tag{1}$$

$$p_B = p_{\tan k} - 0.5\rho_B \left(\frac{m_B}{\rho_B A_B} \right)^2 \tag{2}$$

$$T_B = \frac{1}{c_{p,\tan k}} \left[c_{pB} T_{\tan k} - 0.5 \left(\frac{m_B}{\rho_B A_B} \right)^2 \right] \tag{3}$$

$$\frac{dV_{\tan k}}{dt} = \frac{m_A}{\rho_A} - \frac{m_B}{\rho_B} \tag{4}$$

$$\frac{dT_{\tan k}}{dt} = \frac{-\rho_B c_{p,B} T_{\tan k} \dfrac{dV_{\tan k}}{dt} + q_A - q_B}{\rho_B V_{\tan k} c_{p,B}} \tag{5}$$

$$q_B = c_{pB} T_{\tan k} m_B \tag{6}$$

2. Valve

The Valve is a variable area component controlled by an actuator stroke input, x, provided by a servo modeled in the control system. The maximum stroke, x_{max}, maximum exit area, A_B, discharge coefficient, c_d, effective length, L, and initial flow rate, m, are set by the user. The flow area varies linearly with stroke, with maximum area occurring at maximum stroke. The Valve is governed by Equations 7 and 8.

$$(p_A - p_B) A_B \left(\frac{x}{x_{\max}} \right) = L \frac{dm}{dt} + m \left(\left| \frac{m}{\rho_B A_B \left(\dfrac{x}{x_{\max}} \right) c_d} \right| - \left| \frac{m}{\rho_A A_A} \right| \right) \tag{7}$$

$$T_A - T_B = T_A - \frac{1}{c_{pB}} \left(\frac{q}{m} - 0.5 \left(\frac{m}{\rho_B A_B \left(\dfrac{x}{x_{\max}} \right) c_d} \right)^2 \right) \text{ for } m \neq 0 \tag{8}$$

$$T_A - T_B = 0 \text{ for } m = 0$$

3. Battery

The Battery is an unsteady model of an ideal electrical storage device that balances the energy exiting by a reduction in internal energy. There are neither internal losses nor resistances, and the voltage remains constant. The battery is constructed using elements in Simscape™'s electric foundation library. The user inputs initial energy and voltage.

4. Motor

The Motor converts the electrical energy from the battery to rotational mechanical energy. It is constructed using elements in Simscape™'s electrical and mechanical foundation libraries. The motor is an ideal DC type where rotational speed, ω, is proportional to the voltage applied. The rotor inertia has been included in the model; however, internal resistances and inductances have not. The user inputs the proportionality constant and the moment of inertia of the rotor.

5. Pump

The Pump converts rotational mechanical energy into fluid energy. It is a positive displacement type where volumetric flow is proportional to rotational speed,ω, and total pressure rise is a function of shaft torque, T_s. The mass flow, m, at the inlet and the outlet of the pump are set equal; however, the work performed by the impeller on the fluid is added, leading to an increase in energy, q. The user inputs pump displacement, V, exit area, A_B, volumetric efficiency, η_{vol}, and thermal efficiency, η_{th}, Currently, the efficiencies are required to be constant over the operating range. The Pump is governed by Equations 9 through 13.

$$m_A = m_B \tag{9}$$

$$m_B = \omega V \eta_{vol} \rho_A \tag{10}$$

$$q_B = q_A + \omega\left(\mathrm{T}_S - \mathrm{T}_{ref}\right) \tag{11}$$

$$\mathrm{T}_S = \left[\left(p_B + \frac{\rho_B}{2}\left(\frac{m_B}{\rho_B A_B}\right)^2\right) - \left(p_A + \frac{\rho_A}{2}\left(\frac{m_A}{\rho_A A_A}\right)^2\right)\right]\frac{\eta_{vol}}{\eta_{th}} V \tag{12}$$

$$T_B = \frac{1}{c_p}\left(\frac{q}{m} - 0.5\left(\frac{m}{\rho_B A_B}\right)^2\right) \text{for } m \neq 0$$
$$T_B - T_{ref} = 0 \text{ for } m = 0 \tag{13}$$

6. Pipe

The Pipe component is a generic pipe section of constant area, A. The momentum equation includes terms for wall friction, f, and dynamic head loss, k, allowing it to be used to model a wide variety of geometries (straight sections, elbows, etc). The user inputs length, L, hydraulic diameter, D_H, surface roughness height, ε, dynamic head loss factor, k, and initial flow rate. Area is inherited from the upstream component. The Pipe is governed by Equations 14 through 17.

$$\left(p_A - p_B\right)A = L\frac{dm}{dt} + m\left(\left|\frac{m}{\rho_B A}\right| - \left|\frac{m}{\rho_A A}\right|\right) + \frac{k}{2}m\left|\frac{m}{A}\right|\left(\frac{2}{\rho_A + \rho_B}\right) + \frac{f}{2}\frac{L}{D_H}m\left|\frac{m}{2A}\right|\left(\frac{1}{\rho_A} + \frac{1}{\rho_B}\right) \tag{14}$$

$$\mathrm{Re} = \frac{1}{2}\left(\frac{m}{A}\frac{D_H}{\mu_A} + \frac{m}{A}\frac{D_H}{\mu_B}\right) \tag{15}$$

$$\frac{1}{f^{0.5}} = -1.8\log\left(\frac{6.9}{\mathrm{Re}} + \left(\frac{\varepsilon/D_H}{3.7}\right)^{1.11}\right) \tag{16}$$

$$T_A - T_B = T_A - \frac{1}{c_p}\left(\frac{q}{m} - 0.5\left(\frac{m}{\rho_B A}\right)^2\right) \text{for } m \neq 0$$
$$T_A - T_B = 0 \text{ for } m = 0 \tag{17}$$

7. Area Change

The Area Change component includes a wall pressure force term in the momentum equation to model area changes. The pressure force is determined from the average of the inlet and outlet pressures. For large area changes, accuracy can be improved by placing a number of smaller area change components in series. The user inputs passage length, L, exit area, A_B, and initial flow rate. Inlet area, A_A, is inherited from the upstream component. The Area Change is governed by Equations 18 and 19.

$$(p_A - p_B)A_B = L\frac{dm}{dt} + m\left(\left|\frac{m}{\rho_B A_B}\right| - \left|\frac{m}{\rho_A A_A}\right|\right) + \left(\frac{p_A + p_B}{2}\right)(A_A - A_B) + \frac{f}{2}\frac{L}{D_H}\frac{m}{2}\left|\frac{m}{\rho_B A_B} + \frac{m}{\rho_A A_A}\right| \tag{18}$$

$$T_A - T_B = T_A - \frac{1}{c_p}\left(\frac{q}{m} - 0.5\left(\frac{m}{\rho_B A}\right)^2\right) \text{for } m \neq 0$$
$$T_A - T_B = 0 \text{ for } m = 0 \tag{19}$$

8. Fuel Injector

The Fuel Injector component also models an area change. However, it defines flow area in terms of flow number, *FN*, which is more commonly associated with fuel injectors. The flow number is defined for SI units in Equation 20 . The Fuel Injector is governed by Equations 21 and 22.

$$FN = \frac{m_f}{\sqrt{\Delta p \rho}} \tag{20}$$

$$p_A - p_B = \left(\frac{m}{FN}\right)^2 / \rho_B \tag{21}$$

$$T_A - T_B = T_A - \frac{1}{c_p}\left(\frac{q}{m} - 0.5\left(\frac{m}{\rho_B FN}\right)^2\right) \text{for } m \neq 0$$
$$T_A - T_B = 0 \text{ for } m = 0 \tag{22}$$

9. Flow Sink

The Flow Sink component provides a static pressure boundary for subsonic flow ($v_{sonic} \leq 1$) or a mass flow boundary for supersonic flow ($v_{sonic} > 1$) at an outlet of the flow network. A Flow Sink is required at each location where flow exits the network. There are no user inputs required. These sinks interface with the propulsion system to obtain downstream static pressure. Inlet flow area and fluid properties are obtained from the upstream component. The Flow Sink is governed by Equation 23.

$$p = p_{downstream} \text{ for } \left(\frac{m}{\rho A}\right) \leq v_{sonic}$$
$$m = \rho v_{sonic} A \text{ for } \left(\frac{m}{\rho A}\right) > v_{sonic} \tag{23}$$

10. Flow Tee

The Flow Tee component models the separation of a flow into two flows or the merging of two flows into one. Static pressure is equal for all three streams. The user specifies areas for streams B and C. Area A is provided by the upstream component. The Flow Tee is governed by Equations 24 through 27.

$$m_A = m_B + m_C \tag{24}$$

$$q_B = q_A \frac{m_B}{m_A}$$
$$q_C = q_A \frac{m_C}{m_A} \tag{25}$$

$$p_B = p_A$$
$$p_C = p_A \tag{26}$$

$$\left.\begin{aligned} T_B &= \frac{1}{c_p}\left(\frac{q}{m} - 0.5\left(\frac{m}{\rho_B A}\right)^2\right) \\ T_C &= \frac{1}{c_p}\left(\frac{q}{m} - 0.5\left(\frac{m}{\rho_C A}\right)^2\right) \end{aligned}\right\} \text{for } m \neq 0$$
$$\left.\begin{aligned} T_B &= 0 \\ T_C &= 0 \end{aligned}\right\} \text{for } m = 0 \tag{27}$$

11. Panel

The Panel is a multi-domain component that models compressible flow and heat transfer through liner walls using a lumped parameter approach that accounts for convection, conduction, and thermal mass, as shown in Figure 5. As shown, convection heat transfer is applied at the convective interfaces between the panel and the coolant/fuel and the panel and the propulsion system hot gas. The hot gas path convection coefficient is calculated in the Propulsion System model. Conduction is applied through the panel thickness.

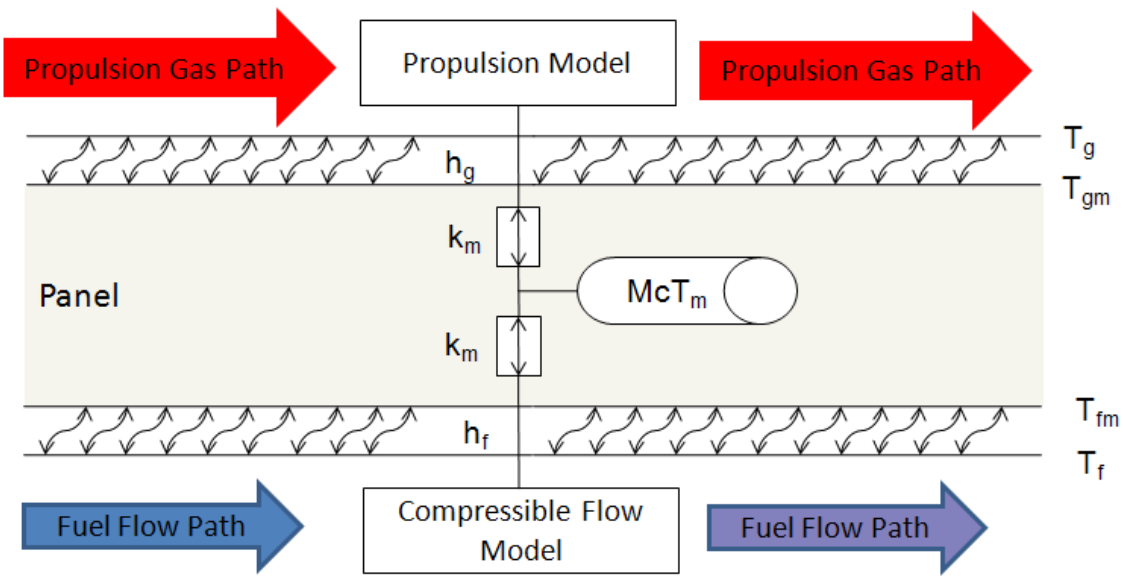

Figure 5. Schematic of Panel Heat Transfer

The fuel flow path of the panel is in the compressible flow domain and is similar to the pipe. The momentum equation includes terms for wall friction, *f*, and dynamic head loss, *k*, allowing it to be used to model a wide variety of geometries. The compressible flow portion of the Panel is governed by Equations 28 through 33.

$$m = m_B = m_A \tag{28}$$

$$q_B = q_A + q_Q \tag{29}$$

$$(p_A - p_B)A = L\frac{dm}{dt} + m\left(\left|\frac{m}{\rho_B A}\right| - \left|\frac{m}{\rho_A A}\right|\right) + \frac{k}{2}m\left|\frac{m}{A}\right|\left(\frac{2}{\rho_A + \rho_B}\right) + f\frac{L}{D_H}m\left|\frac{m}{2A}\right|\left(\frac{1}{\rho_A} + \frac{1}{\rho_B}\right) \tag{30}$$

$$\mathrm{Re} = \frac{1}{2}\left(\frac{m}{A}\frac{D_H}{\mu_A} + \frac{m}{A}\frac{D_H}{\mu_B}\right) \tag{31}$$

$$\frac{1}{f^{0.5}} = -1.8\log\left(\frac{6.9}{\mathrm{Re}} + \left(\frac{\varepsilon/D_H}{3.7}\right)^{1.11}\right) \tag{32}$$

$$T_A - T_B = T_A - \frac{1}{c_p}\left(\frac{q}{m} - 0.5\left(\frac{m}{\rho_B A}\right)^2\right) \text{ for } m \neq 0$$
$$T_A - T_B = 0 \text{ for } m = 0 \tag{33}$$

The purpose of the Panel is to provide a path for energy (heat) to flow into and out of the fuel. Since mass and energy are conserved across a component's ports, a thermal tee had to be placed inside the panel to allow energy in the form of heat to be added. This tee conserves mass flow but allows energy to flow into and out of the compressible flow path through the flow path walls.

Convection at the flow path wall is the interface between the compressible flow domain and the thermal domain. The convection coefficient at the wall, h_f, is variable (not set by the user) and is determined from the flow properties using the Dittus-Bolter correlation shown in Equations 34 and 35.

$$Nu_D = 0.023\,\mathrm{Re}_D^{0.8}\,\mathrm{Pr}^{0.4} \tag{34}$$

$$Nu_D = \frac{h_f D_H}{k_f} \tag{35}$$

This convection coefficient is communicated to a variable convective heat transfer element in the thermal domain. This element determines thermal energy flow into and out of the fuel flow stream based on the heat transfer coefficient, the bulk fuel temperature, T_f, and the fuel side panel temperature, T_{fm}.

The panel itself is made of two conduction elements with a thermal mass element located between them. Thermal conductivity through the panel, k_f, is constant and is set by the user. Thermal mass of the panel, M, is determined from panel geometry and material properties, also input by the user.

The Panel interfaces with the Propulsion System using Simulink™ signals. The panel outputs the panel temperature, T_{gm}, to the Propulsion system. The Propulsion System uses this temperature and the hot gas side heat transfer coefficient, h_g, calculated using the Dittus-Bolter correlation and local gas path conditions to calculate thermal energy transfer from the Propulsion System to the Panel. The hot gas path side heat transfer coefficient calculation was added to the Propulsion System to minimize the amount of data transfer at the system interface.

The user inputs hot side area normal to flow, thickness, material properties, coolant pipe geometry, and dynamic head loss factors.

IV. System Model Verification

Verification of the Thermal Management and Fuel System was conducted on the TBCC configuration shown in Figure 6. This system was integrated with the Propulsion System and Hydraulic and Kinematic System so that a complete test, including interfaces, could be conducted. Fuel is used to cool a turbojet afterburner liner and a Dual Mode SCRAMJET (DMSJ) liner within the Thermal Management and Fuel System. A variable speed pump driven

by an electric motor circulates fuel through the liners and vehicle fuel tank continuously, independent of the mode of operation. A controller adjusts the speed of the pump to maintain a set pressure in the system as flow demand varies. Three control valves divert a portion of the fuel flow into the turbojet main burner, turbojet afterburner, and the DMSJ. A fourth control valve varies the flow returning to the tank and is adjusted to maintain a maximum fuel temperature of 500 °K at high power conditions and a minimum flow rate at low power conditions. This system was chosen for its simplicity, but allows verification of all the physical processes that occur in more complex systems.

There is no test data available on this system. Verification consisted of confirming a balance of mass and energy across the system boundaries and observing the proper dynamic trends in fuel and liner temperature as gas path temperatures changed due to changes in flight conditions and mode of operation.

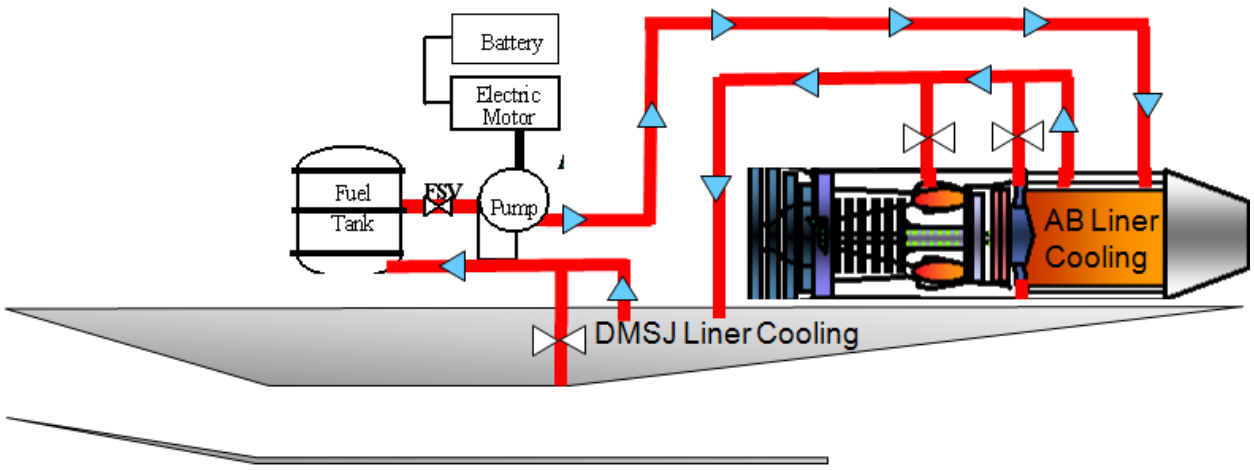

Figure 6. Thermal Management and Fuel System Used in Verification

The results of the mass and energy balance are shown in Table 2. Data was obtained at a number of flight and operating modes with the system running in thermal and mechanical equilibrium. There is excellent agreement, within 0.1%, between the mass and energy entering and exiting the system.

Table 2. Thermal Management and Fuel System Mass and Energy Balance

Test Point		1	2	3
Flight Mach Number		2.5	3.75	3.75
TurboJet Operation		Max Power (A/B on)	Max Power (AB on)	Mil Power (AB off)
DMSJ Operation		Off	Off	PLA40
Mass In	kg/s	1.54870	1.53140	1.36770
Mass Out	kg/s	1.54874	1.53141	1.36770
Mass Differential		-0.003%	0.0005%	0.000%
Energy In	J/s	1.2877e6	1.7086e6	2.1124e6
Energy Out	J/s	1.2879e6	1.7077e6	2.1123e6
Energy Differential		-0.017%	0.047%	0.003%

The flight Mach numbers and operating modes used during the dynamic verification are shown in Figure 7. This simulated the vehicle accelerating from Mach 2.5 to 4.7, and includes the critical transition period at Mach 3.75 and parts of the turbojet only and DMSJ only operation.

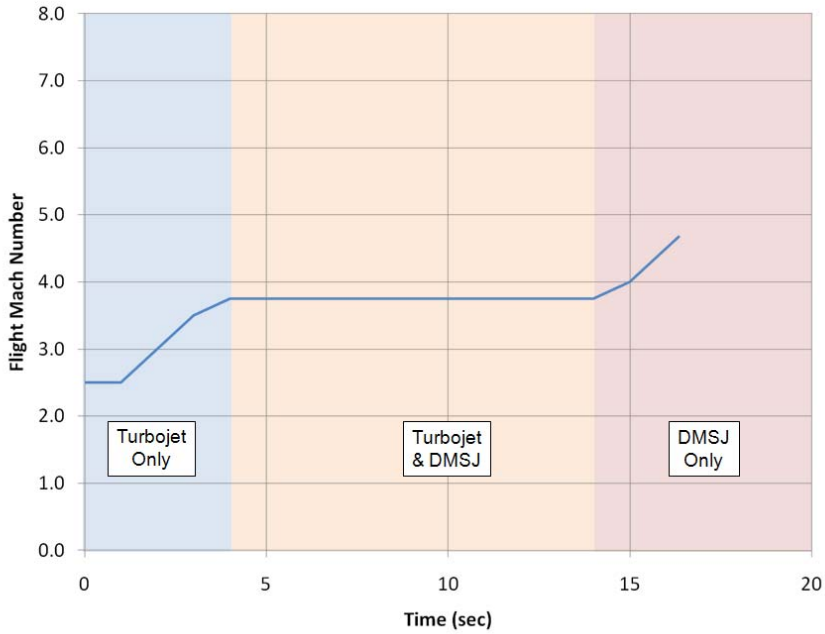

Figure 7. Verification Flight Mach Numbers and Operating Conditions

Liner surface temperatures and fuel temperatures entering the turbojet and DMSJ are shown in Figure 8 and Figure 9, respectively. At time 0, during turbojet only operation, the temperature in the afterburner is significantly higher than the temperature in the DMSJ gas path, as reflected in the liner temperatures. However, the fuel entering the turbojet is cooler than the fuel at the DMSJ fuel injector since it does not pass through the DMSJ liner, as previously shown in Figure 6.

As the vehicle accelerates during turbojet only operation, the gas path temperatures of the two streams rise as Mach number increases due to the increase in the total temperature of the air, as indicated by liner temperatures. The afterburner gas path temperature does not rise as rapidly, though, as the control system reduces fuel flow to avoid exceeding maximum material temperatures.

At approximately three seconds the total temperature of the fuel entering the DMSJ exceeds the maximum allowable fuel temperature of 550°K. The controller adjusts the control valve to increase recirculation fuel flow to maintain that temperature. The fuel temperature then remains relatively constant at the DMSJ as Mach number increases. The turbojet fuel flow temperature, however, decreases, as the heat removed from the afterburner liner is transferred to a greater amount of recirculation flow. This is also reflected in the afterburner liner temperature.

At five seconds, as the low-speed flow path shuts-down during transition, the fuel temperature entering the turbojet can be seen to drop, initially as fuel is cut-off to the afterburner, and then as the turbine spools-down. The DMSJ fuel flow maintains its maximum temperature until about 13 seconds when fuel flow to the DMSJ starts to increase at a faster rate for the start of acceleration. At this point, the control system is not responding fast enough with increased fuel flow. This leads to the temperature drifting above the designated maximum allowable temperature.

These observations verify the proper dynamic trends in fuel and liner temperature as gas path temperatures changed due to changes in flight conditions and mode of operation. Although the fuel temperature exceeding the maximum limit is not desirable from an operational standpoint, it does demonstrate the ability of the tool to asses Thermal Management and Fuel System sizing as well as Control System design.

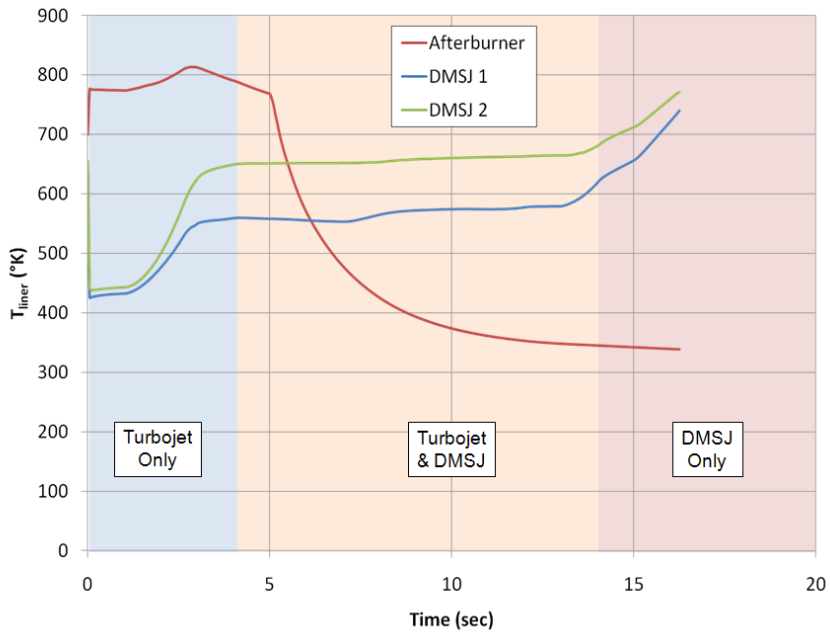

Figure 8. Liner Surface Temperatures Verse Simulation Time

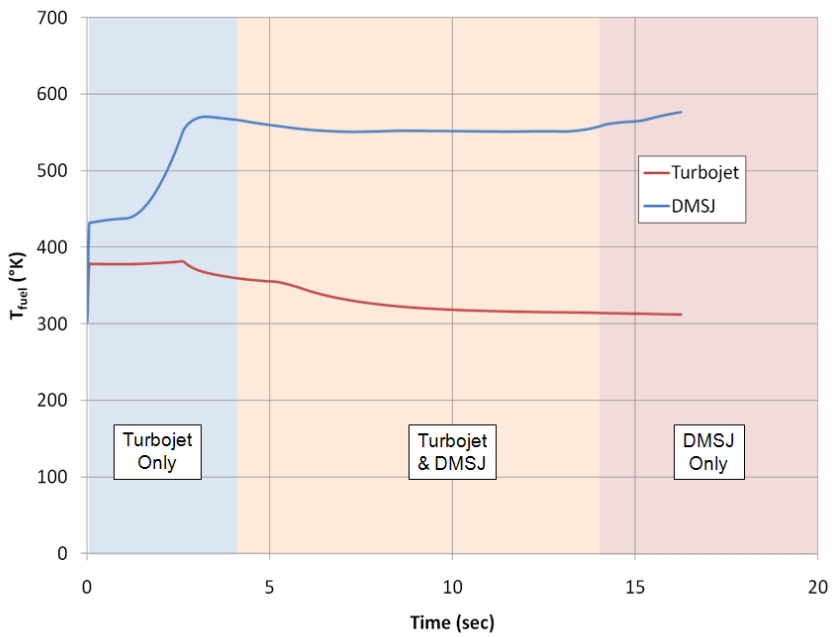

Figure 9. Fuel Temperature Response to Acceleration

V. Conclusion

Tools and procedures have been developed for numerical dynamic system modeling of a TBCC propulsion system, including the thermal management for both the low-speed and high-speed flow paths. These tools have been incorporated within the High Mach Transient Engine Cycle Code (HiTECC) to computationally simulate a Turbine Based Combined Cycle (TBCC) propulsion system. HiTECC is a dynamic turbine engine model built in

Simulink™ to provide real time engine performance predictions during vehicle-wide high-speed transient studies. The model is built on a component level to provide flexibility to model a wide range of engine cycles and to provide internal engine performance data.

The Thermal Management and Fuel System is a detailed physical model of the cooling and fuel system used to manage the heat load generated by and deliver the fuel required by the dual-mode scramjet and afterburning turbojet propulsion systems. This model has been developed assuming fuel as the coolant. The Thermal Management and Fuel System simulates fuel flow, fluid energy, and thermal energy transfer for both the low-speed and high-speed flow paths. The model was developed to interface with the Propulsion System to predict real-time thermal loads on the gas path surfaces. This model couples a transient flow model with a transient thermal model for determining the dynamic response of the fuel and gas path hardware. A one-dimensional compressible flow solver allows a variety of fuels, including hydrogen, to be modeled.

It has been verified that the Thermal Management and Fuel System developed here can simulate all modes of supersonic operation, including mode transition, for a Turbine-Based Combined Cycle (TBCC) propulsion system. The system has been tested in a simulation of a TBCC vehicle accelerating from Mach 2.5 to 4.7 with mode transition at Mach 3.75. Mass and energy balance across the system to within 0.1% over the entire fight range. Dynamic fuel and gas path liner predictions follow trends consistent with expectations for this type of propulsion system.

VI. Future Plans

The development of the TBCC propulsion system dynamic model significantly extends the state-of-the-art for TBCC vehicles by providing a numerical simulation of the propulsion systems for use in future control system development. Future work included in *SPIRITECH*'s TBCC Simulation Model development program includes further integration of the individual systems into the overall HiTECC simulator. The integrated simulator will be used to provide a numerical simulation of the systems, interactions, and transient responses affecting the ability of the propulsion system to transition from turbine-based to ramjet/scramjet-based propulsion.

VII. Acknowledgment

The work documented in this paper is the product of a NASA NRA award under contract NNC08CA55C. The authors would like to thank Dr. Thomas J. Stueber of NASA Glenn Research Center for his guidance and support throughout this effort.

VIII. References

[1] E.J. Gamble , D.A. Haid , and S. D'Alessandro, "Dual-Mode Scramjet Performance Model for TBCC Simulation", AIAA-2009-5298, August 2009.

[2] E.J. Gamble , D.A. Haid , and S. D'Alessandro, "Kinematic and Actuation System Model for TBCC Dynamic Simulation", AIAA-2010, July 2010 (submitted for publication).

[3] SUPERTRAPP, NIST ThermoPhysical Properties of Hydrocarbon Mixtures Database, Software Package, Version 3.1, National Institute of Standards and Technology, Gaithersburg, MD, 2003.

[4] R. C. Rice, J. L. Jackson, J. Bakuckas, and S. Thompson. *Metallic Materials Properties Development and Standardization (MMPDS-01),.* United States Department of Transportation, Federal Aviation Administration, Office of Aviation Research, Washington D.C., 2003.

[5] *Aerospace Structural Metals Handbook*. Purdue Research Foundation, West Lafayette, IN 47907.