INTERFACING SINDA/FLUINT WITH ROCETS

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ABSTRACT

A complete thermal and fluid systems analysis for a Rocket-Based Combined Cycle (RBCC) type vehicle would optimally link the cycle analysis of the vehicle with the thermal and fluid systems analysis of the vehicle. Furthermore it would be advantageous if the cycle analysis could be dynamically linked to the thermal and fluids systems analysis. This would avoid the repetitive and tedious process of manually inputting the results of the cycle analysis as boundary conditions in the thermal and fluids systems analysis, and subsequently inputting those results as boundary conditions in the cycle analysis until a converged solution is achieved. The goal of this paper is to illustrate such an interface between the ROCket Engine Transient Simulator (ROCETS), a cycle analysis code, and a thermal and fluid systems analysis code, SINDA/FLUINT.

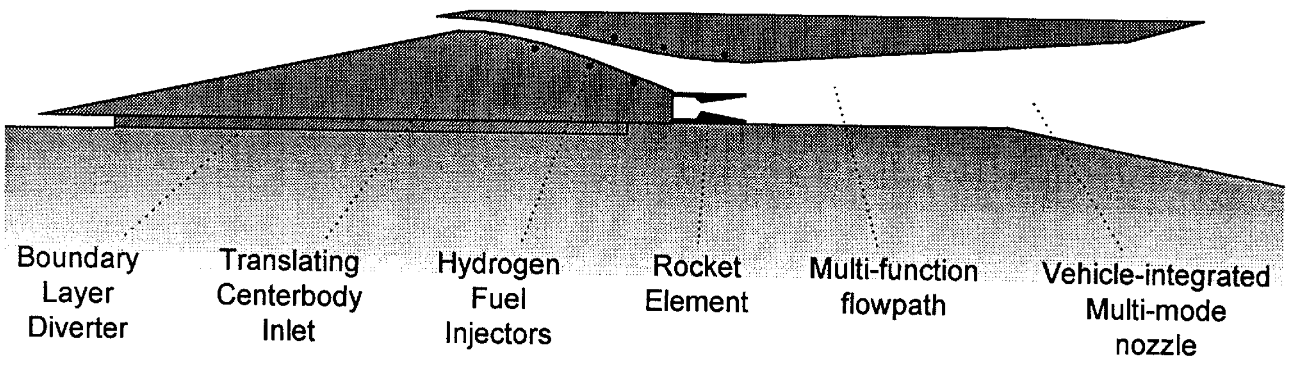
INTRODUCTION

The reasoning behind choosing ROCETS for the cycle analysis code and SINDA/FLUINT for the thermal and fluids system analysis code is simultaneously multi-faceted and quite simple. ROCETS is unique in that it enables the user to input "modules" representing various components of the vehicle's system. In the case of an RBCC-type vehicle, the user can input tailor made subroutines representing the inlet, rocket, combustor, mixer, and or nozzle. ROCETS runs these subroutines in a user defined order and performs any system balances that are required. SINDA/FLUINT is an extremely versatile thermal and fluid systems analysis code that has many features to model the active and passive cooling systems of an RBCC-type vehicle. Such features include the ability to model multiphase flow and heat transfer, and turbines and pumps. One of the main advantages in using SINDA/FLUINT is that it can easily incorporate user-defined subroutines. In this case the user-defined subroutine would be ROCETS. Finally, the simple reason for using the respective codes ROCETS and SINDA/FLUINT is that they are available and more or less ready to use.

This paper will describe the challenges in interfacing ROCETS and SINDA/FLUINT, and the process through which they communicate. In discussing these points, it is assumed the reader has a rudimentary working knowledge of ROCETS and SINDA/FLUINT.

ROCETS PROCESS DESCRIPTION

There are five modules implemented in the ROCETS code that describe the cycle analysis for an RBCC-type vehicle. They represent the inlet, rocket, combustor, mixer, and nozzle. A depiction of such a vehicle with these components is shown in Figure 1. The hierarchy in which the respective modules are called is illustrated in Figure 2. The various modes of the vehicle's operation are outlined in Table 1.



Four operating modes from lift-off to orbit:

1) Ejector-Ramjet
2) Subsonic combustion ramjet
3) Supersonic combustion ramjet
4) High area-ratio rocket

Figure 1. RBCC-Type Vehicle

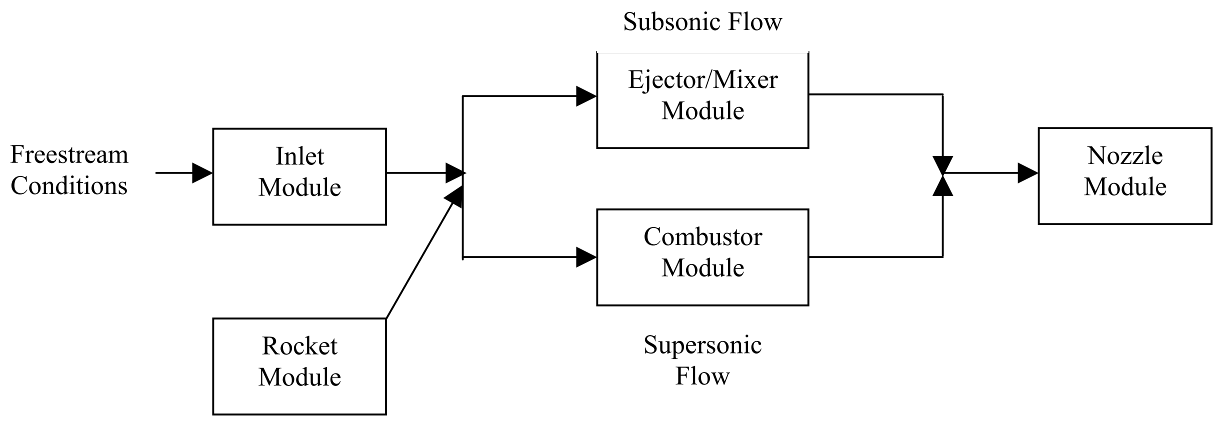


Figure 2. ROCETS Cycle Layout

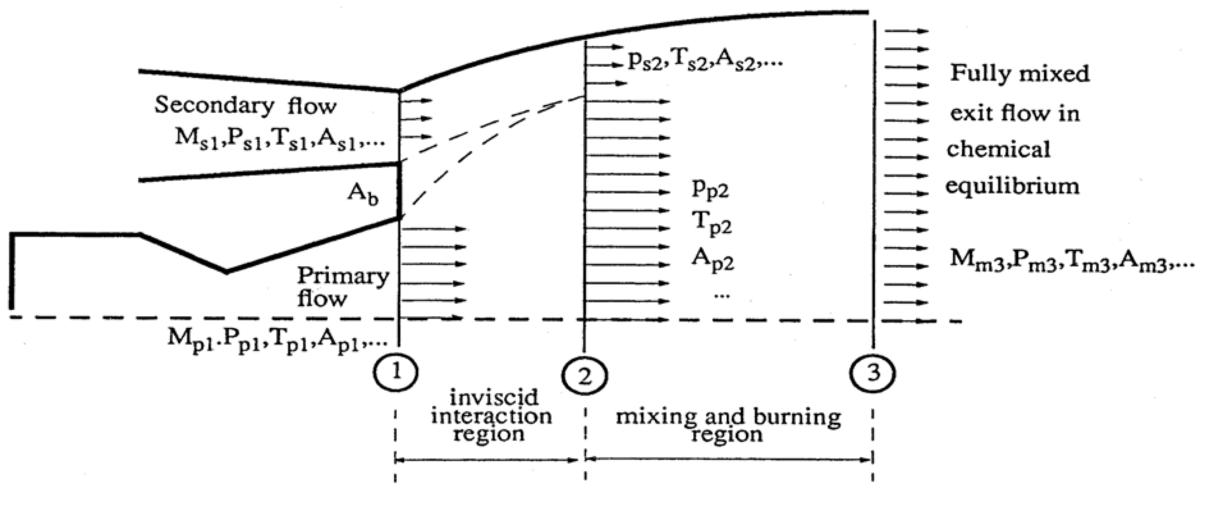
	Mach Number	Inlet	Ejector/Mixer	Combustor	Rocket	Nozzle
Mode 1	0.0 – 2.5	ON	ON	OFF	ON	ON
Mode 2-3	2.5 – 12.0	ON	OFF	ON	OFF	ON
Mode 4	12.0 – 25.0	OFF	OFF	OFF	ON	ON

Table 1. Vehicle Modes of Operation

The inlet module uses the LArge Perturbation INlet (LAPIN) code. LAPIN is a one dimensional transient inlet code that can model both supersonic and subsonic freestream and outlet conditions. Its many versatile modeling abilities include moving shocks, bleeds and bypasses, and rotating and translating centerbodies. LAPIN is modified for use in ROCETS to accommodate the modeling of RBCC-type vehicles specifically in the hypersonic regime. Normally the user inputs a constant value of gamma (ratio of specific heats) into LAPIN and obtains a solution based on that constant value of gamma. However when LAPIN is used in ROCETS, a constant value of gamma is still employed, but it is an average value for the inlet calculated from the flow properties. Flow properties are determined by the Chemical Equilibrium Code (CSDTTP). On the first pass through the inlet a “guessed” value of gamma is used to obtain a solution. From this solution an average value of gamma is recalculated based on the flow properties. This value of gamma is then used as the new “guessed” value of gamma for the inlet whereupon a new solution is obtained. This iterative process is continued until gamma no longer changes. The second modification made to LAPIN for use in ROCETS for RBCC-type vehicles is to accommodate non-axisymmetric area distributions through inlets. LAPIN normally can model two-dimensional and axisymmetric flows. Area modification factors are incorporated into the axisymmetric area terms. These factors are based on the “real” area distribution through the inlet.

The rocket module uses the Chemical Equilibrium Code (CSDTTP) to model the rocket component of the vehicle. The rocket module can model the rocket component as “one-dimensional” by discretizing the domain as a function of area ratio. This allows for greater refinement in calculating heat transfer coefficients through the rocket.

The combustor and ejector/mixer modules also use the Chemical Equilibrium Code (CSDTTP). Unfortunately they cannot simulate any “one-dimensionality”, so to speak, only a single thermodynamic state. This leads to a poor resolution of heat transfer distribution in that region of the vehicle. According to Table 1. The combustor does not operate when the rocket is “on”. The ejector/mixer does operate when the rocket is “on”. A schematic of the mixer is shown in Figure 3. The secondary flow from the inlet (station 1) mixes with the primary flow from the rocket (station 1).


$p_{s2}, T_{s2}, A_{s2}, \ldots$
Fully mixed exit flow in chemical equilibrium
Secondary flow
$M_{s1}, P_{s1}, T_{s1}, A_{s1}, \ldots$
A_b
P_{p2}
T_{p2}
A_{p2}
...
Primary flow
$M_{m3}, P_{m3}, T_{m3}, A_{m3}, \ldots$
$M_{p1}, P_{p1}, T_{p1}, A_{p1}, \ldots$
1
2
3
inviscid interaction region
mixing and burning region

M = Mach Number, P = Pressure, T = Temperature, A = Area

Subscripts: p = primary flow, s = secondary flow, m = mixed flow

Figure 3. Schematic of Ejector/Mixer

Finally, the nozzle module uses the Chemical Equilibrium Code (CSDTTP) to model this vehicle component. This model can also be made "one-dimensional" by discretizing the domain as a function of area ratio.

ROCETS fullest capabilities are utilized for subsonic freestream conditions (mode 1). In this mode ROCETS performs a mass flow balance between the inlet and the ejector/mixer. At the start of the run, an initial guess on either the exit mach number or exit pressure of the inlet is input by the user. The inlet module (LAPIN) calculates a mass flow rate based on one of these exit boundary conditions. This calculated mass flow rate value as well as the exit boundary condition of pressure or Mach number is sent to the ejector/mixer module as a "guess". The ejector/mixer module then calculates a new mass flow rate so that the exit of the mixer is choked. ROCETS continues to perturb the inlet exit boundary condition of pressure or Mach number until the calculated values of mass flow from the inlet and ejector/mixer modules match.

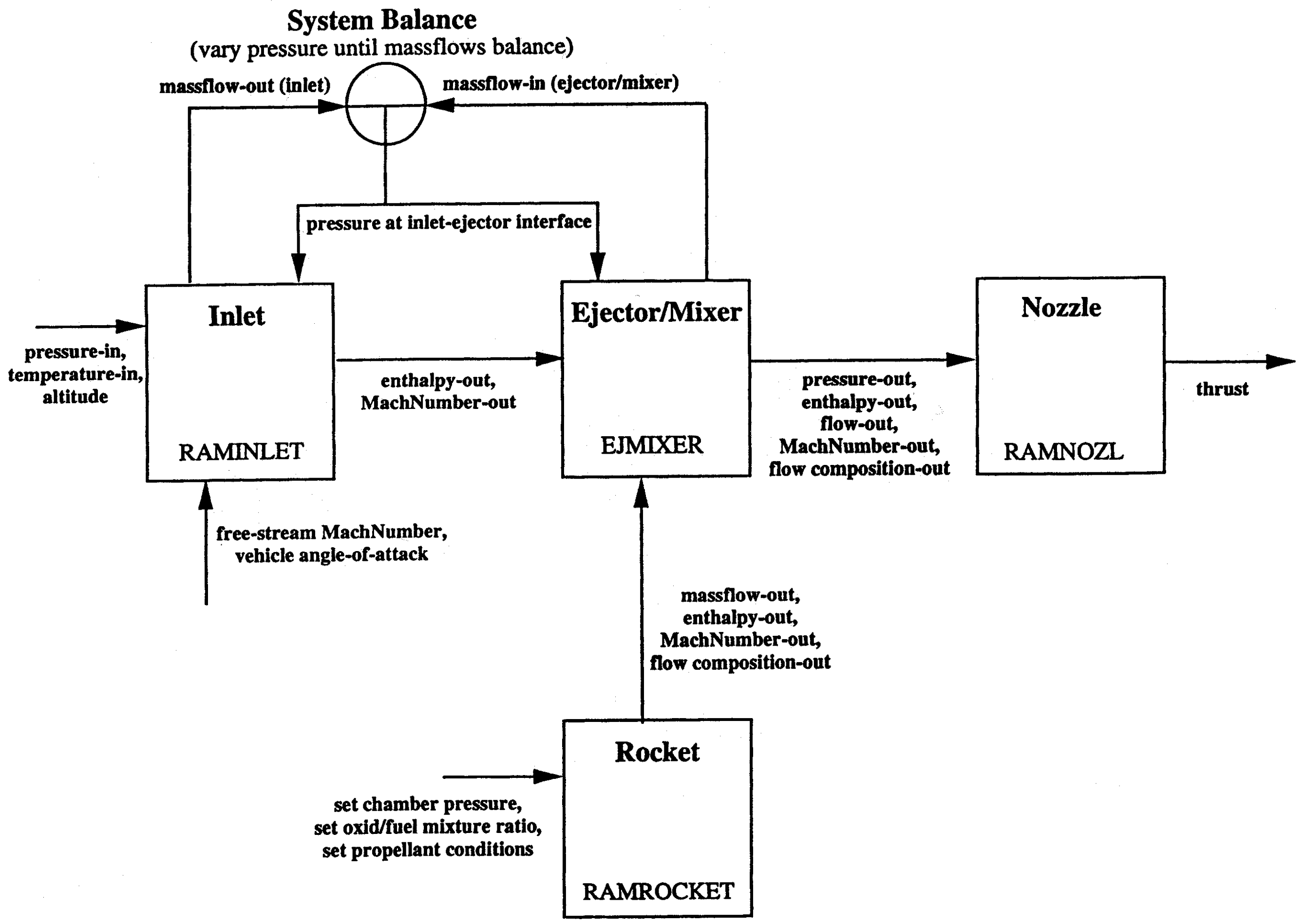


Figure 4. ROCETS System Configuration for Subsonic Freestream Conditions

For supersonic flow no such balancing is required, i.e., the combustor "accepts" the downstream conditions of the inlet and the combustion is supersonic.

SINDA/FLUINT

SINDA/FLUINT is used to model the active cooling system of the vehicle which also serves as the fuel feed system of the vehicle. The detailed components of the feed system such as the pumps and turbines have not been incorporated into the model yet. They will be incorporated in future models. The cooling fluid is hydrogen and properties are generated for SINDA/FLUINT using GASPLUS. Currently the mass flow rate of the cooling system set is set by the user. Future models will determine an optimal flow rate through the system to yield an appropriate power balance in the cycle analysis. Thus the SINDA/FLUINT model of the cooling system to date is a one dimensional model represented by a bundle of tubes with the hydrogen flowing through it. These tubes pass over each of the components (i.e., inlet, rocket, combustor, ejector/mixer, nozzle) of the vehicle. Heat conduction through the vehicle “walls” is also modeled

HEAT TRANSFER

Heat rates are calculated in each of the component modules of ROCETS using wall temperatures from SINDA/FLUINT. The heat transfer coefficient, Hc, is calculated in the inlet, mixer/combustor, and nozzle modules using the Colburn Equation:

Hc = Nud*K (1)

where the Nusselt number is defined by:

Nud = 0.023*Re**(4./5.)*Pr**.34 (2)

The heat transfer coefficient, Hc, is calculated in the rocket module using the Bartz Equation:

Hc = 0.026 * (W/A)**.8 * (Ts/Tam)**.8 * K**.6 / D**.2 * (Cp/Mu)**.4 * (D/Rc)**.1 (3)

where the Stanton number is defined by:

St = Stthrt*(D/Rc)**(.1)*Ar**(-.9)*(Ts/Tam)**.8 (4)

or

Hc = St * W/A * Cp (5)

given that

W	= Mass Flow Rate
Ts	= Static Temperature
Twall	= Wall Temperature
Tam	= Arithmetic Mean Film Temperature: (Ts+Twall)/2.0
(Ts/Tam)**.8	= Property Correction
K	= Conductivity
Cp	= Specific Heat

Mu	= Viscosity
Re	= Reynolds Number
Pr	= Prandtl Number
Stthrt	= Stanton Number at the Throat: (0.026*Re**-.2*Pr**-.6)
D	= Hydraulic Diameter
Rc	= Radius of Curvature
A	= Cross Sectional Area
Ar	= Cross Sectional Area / Throat Cross Sectional Area
(D/Rc)**.1*Ar**-.9	= Corrects from Throat to Local Geometry

Calculated heat rates are imposed on the SINDA/FLUINT "wall" nodes. SINDA/FLUINT then calculates new wall temperatures which are passed back to the respective ROCETS subroutines. This process continues until SINDA/FLUINT meets convergence criteria for changes in energy and temperature.

RESULTS

The hierarchical structure of the interface between ROCETS and SINDA/FLUINT places ROCETS as a subroutine to SINDA/FLUINT. This is the easiest methodology because of the input file structure of SINDA/FLUINT. The main calling subroutine of ROCETS is called from the OPERATIONS BLOCK of SINDA/FLUINT. A steady-state flow field is first established in ROCETS. Heat rates are calculated based on guessed "wall" temperatures. Then SINDA/FLUINT performs a steady-state analysis on the cooling/feed system with the given heat rates. At the beginning of every iteration in the SINDA/FLUINT analysis, the heat rates on the "wall" are updated by calls to the heat transfer subroutines. The heat rates are continually updated until SINDA/FLUINT converges. Currently the model runs with no update to the initial steady-state flow calculation of the vehicle so as to obtain results in a faster run time. However each component module does have the ability to add heat to or subtract heat from the flow.

The main obstacle in interfacing such a large code, ROCETS, with all the accompanied subroutines representing the vehicle's components, is the overlap of subroutine and common block names. It is helpful when the FORTRAN compiler flags an overlap in subroutine or common block names, otherwise, things will go very awry. Fortunately only a handful of subroutine and common block names need to be altered. Most of these changes are in the utility subroutines used to model the vehicle's components in the cycle analysis. The only ROCETS specific subroutine that needs to be changed for use in SINDA/FLUINT is the subroutine (COMPRS).

Another annoyance in interfacing multiple codes is the duplication of unit numbers. No unit numbers are changed in the ROCETS subroutines interfaced with SINDA/FLUINT. However modifications were made to the unit numbers in the utility subroutines used to model the vehicle's components in the cycle analysis.

To expedite the compilation of the SINDA/FLUINT input file, the entire ROCETS source code is placed in the SINDA/FLUINT library. Basically a new library is created containing the ROCETS source code and the SINDA/FLUINT library is appended to this new library. Only two subroutines from the ROCETS code are placed in the SINDA/FLUINT input file's SUBROUTINE DATA BLOCK. These subroutines, which are created from the ROCETS preprocessor, are the initial guess file of values for the ROCETS run (GUESS), and the subroutine (ROCETS). The subroutine (ROCETS) sets up the unique cycle run determined by the ROCETS configuration file. Subroutine (GUESS) is left out of the SINDA/FLUINT library so that the user may change initial conditions as desired without having to recompile the SINDA/FLUINT library. The subroutine (ROCETS) changes with every new configuration file so it is also advantageous to omit this file from the library. These two files are placed in the same working directory as the SINDA/FLUINT input file.

Another note about the ROCETS routines interfaced with SINDA/FLUINT. The ROCETS program has a set of preprocessing subroutines that process a configuration file which the user constructs. These subroutines are not interfaced with the SINDA/FLUINT library. The user must first, outside of the SINDA/FLUINT environment, run these subroutines to create the (ROCETS) and (GUESS) subroutines respectively. A modification to the subroutine (CPOPEN) is made so that the SIZES.INC file can be copied into the SINDA/FLUINT working directory and the ROCETS RUNIN directory. The SIZES.INC is not created by the ROCETS preprocessing source code but is set by the user as the maximum fixed size.

A final note on the passing of arguments between ROCETS modules. The original intent of ROCETS was to pass all variables through the argument lists of the subroutines. However with the interfacing of large modules to model the vehicle's components this turned out to be quite impossible. Common blocks are used to communicate between these large codes used to represent the inlet, rocket, combustor, ejector/mixer, and nozzle. They are also used in the various property calculation subroutines. Otherwise the argument lists for these modules would have ungodly sizes. Most of these variables would be undesirable and unnecessary system variables and cause the user a lot of stress to book-keep.

CONCLUSIONS

A dynamic interface was successfully created between ROCETS and SINDA/FLUINT to link the thermal and fluid systems analysis to the cycle analysis for a Rocket-Based Combined Cycle (RBCC) type vehicle. Future models will incorporate the use of Thermal Desktop to model the entire vehicle. This way the user can easily visualize the thermal loads on the entire vehicle from the cycle and thermal and fluid systems analysis. Furthermore, future models will also incorporate the pumping and turbomachinery in the fuel feed system, and will also determine an optimal flow rate through the fuel feed system to yield an appropriate power balance in the cycle analysis.