Generalized Fluid System Simulation Program (GFSSP)
Version 6 – General Purpose Thermo-Fluid Network Analysis Software

Alok Majumdar, Andre Leclair, Ric Moore
NASA/Marshall Space Flight Center
&
Paul Schallhorn
NASA/Kennedy Space Center

Thermal Fluids Analysis Workshop (TFAWS)
August 15-19, 2011, Newport News, VA
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  – Pressure Regulator Model with Forward Looking Algorithm
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  – SI Option

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Introduction

• GFSSP stands for Generalized Fluid System Simulation Program
• It is a general-purpose computer program to compute pressure, temperature and flow distribution in a flow network
• It was primarily developed to analyze
  – Internal Flow Analysis of a Turbopump
  – Transient Flow Analysis of a Propulsion System
• GFSSP development started in 1994 with an objective to provide a generalized and easy to use flow analysis tool for thermo-fluid systems
Development History

• Version 1.4 (Steady State) was released in 1996
• Version 2.01 (Thermodynamic Transient) was released in 1998
• Version 3.0 (User Subroutine) was released in 1999
• Graphical User Interface, VTASC was developed in 2000
• Selected for NASA Software of the Year Award in 2001
• Version 4.0 (Fluid Transient and post-processing capability) is released in 2003
• Version 5 (Conjugate Heat Transfer) is released in 2007
Network Definition

GFSSP calculates pressure, temperature, and concentrations at nodes and calculates flow rates through branches.
Program Structure

Graphical User Interface (VTASC)

Input Data File
- Creates Flow Circuit
- Runs GFSSP
- Displays results graphically

Solver & Property Module
- Equation Generator
- Equation Solver
- Fluid Property Program

Output Data File

User Subroutines
- New Physics
  - Time dependent process
  - non-linear boundary conditions
  - External source term
  - Customized output
  - New resistance / fluid option

- New Physics
## Mathematical Closure

<table>
<thead>
<tr>
<th>Unknown Variables</th>
<th>Available Equations to Solve</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pressure</td>
<td>1. Mass Conservation Equation</td>
</tr>
<tr>
<td>2. Flowrate</td>
<td>2. Momentum Conservation Equation</td>
</tr>
<tr>
<td>5. Specie Concentrations</td>
<td>5. Conservation Equations for Mass Fraction of Species</td>
</tr>
</tbody>
</table>
Graphical User Interface
Capabilities

- Steady or unsteady flow
- Compressible or incompressible flow
- Single fluid or mixture
- 25 flow resistance and 33 fluid options
- Options for new components and physics through User Subroutine
- Options for new fluid through table look-up
- Conjugate Heat Transfer
- Interface with Thermal Analysis Code, SINDA-G/PATRAN
- Translator of SINDA/Fluint Model
Additional Capabilities of Version 6

- Fluid Mixture Option with Phase Change
- Pressure Regulator Model with Forward Looking Algorithm
- Prescribed Flow Option
- Two-dimensional Navier-Stokes Solver
- SI Option
• The mixture capability in earlier versions of GFSSP does not allow phase change in any constituent of the mixture

• In liquid propulsion applications, there are situations where one of the constituents is saturated, i.e. mixture of liquid and vapor in equilibrium
  – For example during purging of liquid oxygen by ambient helium, a mixture of helium, LO2 and GO2 exist

• Why is there such a limitation?
  – Because the energy conservation equation of the mixture is solved in terms of temperature
  – For calculating phase change, energy equation for each species must be solved in terms of enthalpy or entropy
Mathematical Formulation

- **Mass Conservation**
  - Mixture Mass
  - Concentration of Species
- **Momentum Conservation**
  - Mixture Momentum
- **Energy Conservation**
  - Temperature option
    - Energy Conservation is formulated in terms of temperature
    - Applicable for gas mixture
  - Enthalpy option – 1
    - Temperature is calculated by an iterative Newton-Raphson method
  - Enthalpy option - 2
    - Separate Energy Equations are solved for Individual Species
    - Applicable for liquid-gas mixture with phase change
Enthalpy Option - 1

Mixture Enthalpy Equation

\[ h_{i,\tau+\Delta\tau} = \frac{\sum_{j=1}^{n} \sum_{k=1}^{n_f} x_{j,k} h_{j,k,\text{MAX}} \left[ -m_{ij}, 0 \right] + \frac{(m h_i)_\tau}{\Delta \tau} + Q_i}{\sum_{j=1}^{n} \sum_{k=1}^{n_f} x_{j,k} \text{MAX} \left[ m_{ij}, 0 \right] + \frac{m_{\tau}}{\Delta \tau}} \]

Temperature Equation

\[ \sum_{k=1}^{n_f} x_{i,k} h_{i,k} \left( p_i, T_i \right) - h_i = 0 \]

Temperature equation is solved iteratively adjusting \( T_i \) until right hand side of Temperature equation becomes zero.
Separate Energy Equation for Individual Species (SEEIS) – Enthalpy Option - 2

\[
\Delta \tau \left( m_i h_{ik} - \frac{p}{\rho_k J} \right) \bigg|_{\tau+\Delta \tau} - \left( m_i h_{ik} - \frac{p}{\rho_k J} \right) \bigg|_{\tau} = \sum_{j=1}^{j=n} \left\{ \text{MAX} \left( -m_{ij}, 0 \right) h_{jk} - \text{MAX} \left( m_{ij}, 0 \right) h_{ik} \right\} + \dot{Q}_{ik} + \left\{ \pm \dot{Q}_{1\rightarrow2}^{HES} \right\}
\]

Transient Term
Advection Term
Source Term
Thermodynamic Properties

• Temperature and other properties of individual species are calculated from node pressure and enthalpy of the species:

\[ T_{ik} = f(p_i, h_{ik}) \]
\[ \rho_{ik} = f(p_i, h_{ik}) \]
\[ \mu_{ik} = f(p_i, h_{ik}) \]
\[ K_{ik} = f(p_i, h_{ik}) \]
\[ C_{p,ik} = f(p_i, h_{ik}) \]

• The nodal properties are calculated by averaging the properties of species:

\[ \rho_i = \sum_{k=1}^{n_f} c_{ik} \rho_{ik} \]
\[ \mu_i = \sum_{k=1}^{n_f} c_{ik} \mu_{ik} \]

• Temperature is currently calculated by averaging based on molar concentration of species
• Alternate method of temperature calculation based on Vapor Liquid Equilibrium for multi-component, multi-phase mixture is in progress
Pogo Accumulator with Charge Line and Dump line

Charge System

Dump System

POGO Accumulator wrapped around LO2 Feed Line
GFSSP Model of Pogo Accumulator & Drain Line
Charging of helium & draining of He-LO2 mixture

Displacement of Oxygen from the Accumulator during charging

Concentrations of Helium and Oxygen in the Dip Tube
Pressure Regulator Model with Forward Looking Algorithm

• In Marching Algorithm, area is guessed and adjusted only once in each time step
• Adjustment of area is calculated based on difference between calculated and desired pressure
• Area adjustment can be done by backward differencing algorithm (Schallhorn-Majumdar) or forward looking algorithm (Schallhorn-Hass)
• Schallhorn-Hass Algorithm has been implemented in GFSSP Version 602
Backward Differencing Algorithm

\[ A_{\text{new}} = A_{\tau} - \frac{\partial A}{\partial p} (p_{\tau} - p_{\text{reg}}) \]

\[ \eta_{\text{relax}} = \text{relaxation factor/reaction lag} \]

\[ \frac{\partial A}{\partial p} \approx \left| \frac{A_{\tau} - A_{\tau-\Delta \tau}}{p_{\tau} - p_{\tau-\Delta \tau}} \right|, \]

\[ A^{*}_{\tau+\Delta \tau} = \begin{cases} \min\left(\left[ A_{\tau} + \eta_{\text{relax}} (A_{\text{new}} - A_{\tau}) \right] A_{\text{max}} \right), \\
\max\left(\left[ A_{\tau} + \eta_{\text{relax}} (A_{\text{new}} - A_{\tau}) \right] 0 \right) \end{cases} \]

where,

\[ A_{\text{new}} = A_{\tau} \left( \frac{p_{\text{reg}}}{p_{\tau}} \right)^3 \left( e^{\left( \frac{p_{\text{reg}}}{p_{\tau}} - 1 \right)} \right) \],
Application of Forward Looking Algorithm

Pressure History
(Schallhorn & Haas Algorithm)

Tank Pressure

Note oscillations over time

Pressure downstream of regulator
Fixed Flow Option

• A new branch option has been introduced to fix flowrate in a given branch
• The fixed flow branch can only be located adjacent to a Boundary Node
• For unsteady option, a history file will be needed to specify flowrate and area at all timesteps
• With this new option a user can prescribe either pressure or flowrate as boundary condition
• Flow Regulator option is also available in unsteady mode to fix flowrate in an internal branch
Algorithm for Fixed Flow Option (Schallhorn)

\[ \Delta p = A + C \dot{m} \dot{m} \]

where \( A = \alpha \dot{m} \dot{m} \); \( C = -\alpha \); where \( \alpha = 1 \times 10^{25} \)

Substituting \( A \) and \( C \), one gets:

\[ \dot{m} = \frac{\dot{m}}{\dot{m}} \]
New Resistance Option – Fixed Flow
Properties of Fixed Flow Option
Results of Fixed Flow Option
Two-dimensional Navier-Stokes Solver

- Higher fidelity solutions are often needed that are not within the capacity of system level codes.
- GFSSP’s momentum equation has been extended to perform multi-dimensional calculation.
Shear Driven Square Cavity Centerline Velocity Distribution

Dimensionless Height

Dimensionless Velocity

GFSSP Prediction (7x7 Grid)

Burggraf’s 51x51 Grid Prediction (1966)

Velocity Field and Pressure Contours

Predicted Stream Traces
SI Option

- SI Option is for input/output
- GFSSP solver works in Engineering Unit
- User Subroutine must be in Engineering Unit
Concluding Remarks

• GFSSP Version 6 will have additional capabilities to model:
  – Fluid Mixture Option with Phase Change
  – Pressure Regulator Model with Forward Looking Algorithm
  – Prescribed Flow Option
  – Two-dimensional Navier-Stokes Solver
  – SI Option

• GFSSP is available (with no cost) to all Federal Government Organizations and their Contractors

• Concepts/NREC has the license for commercial distribution to domestic and international Companies or Universities

• A process is in work to make an educational version available to all Accredited US Universities for teaching and research
Acknowledgement

- The authors wish to acknowledge Melissa Van Dyke of NASA/MSFC and KSC’s Launch Service Program for the support of the work.
References

1. Generalized Fluid System Simulation Program - Majumdar; Alok Kumar, Bailey; John W. ; Schallhorn; Paul Alan ; Steadman; Todd E. , United States Patent No. 6,748,349, June 8, 2004


References


