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

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Thermal Fluids Analysis Workshop (TFAWS)
August 15-19, 2011, Newport News, VA

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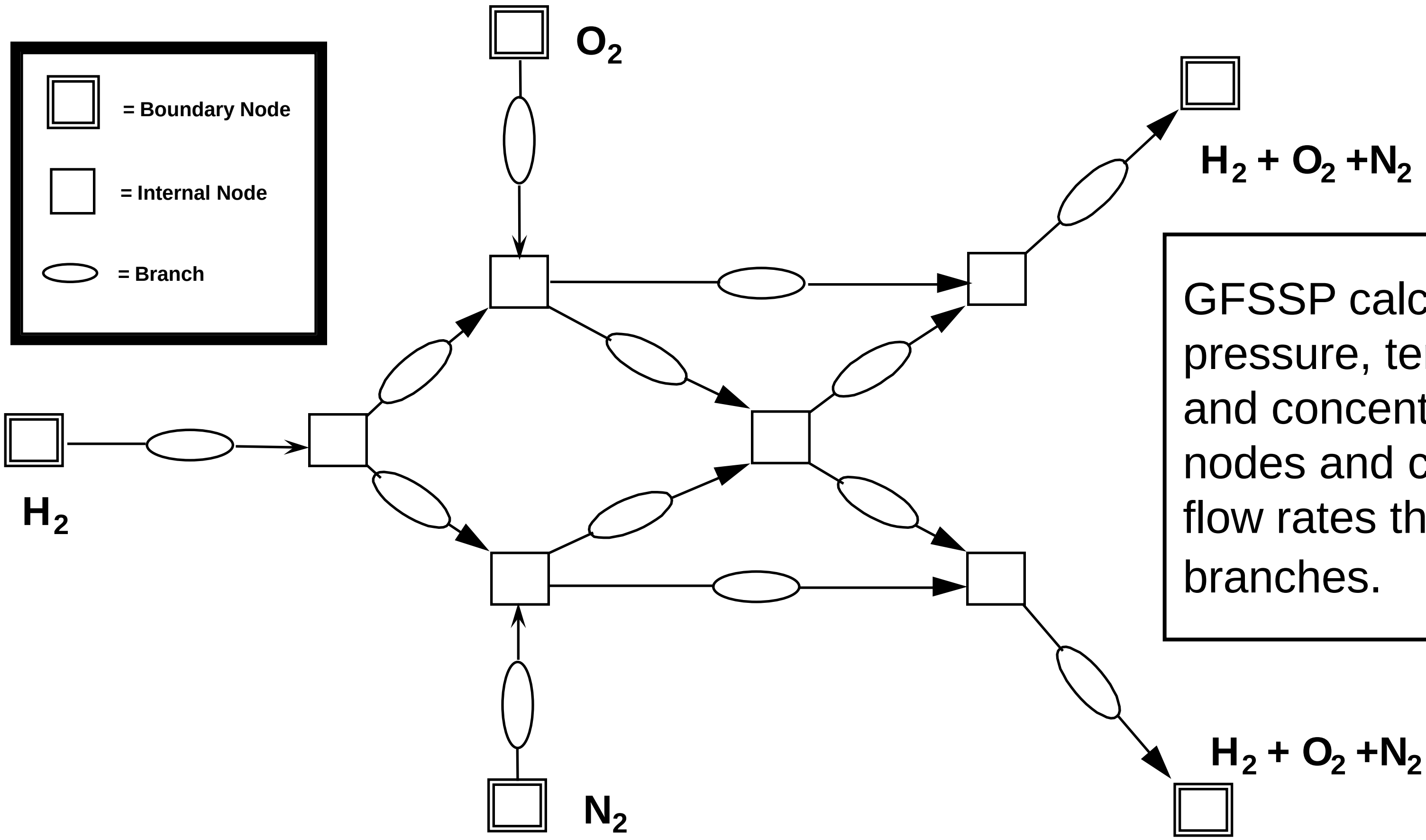
Introduction

- 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

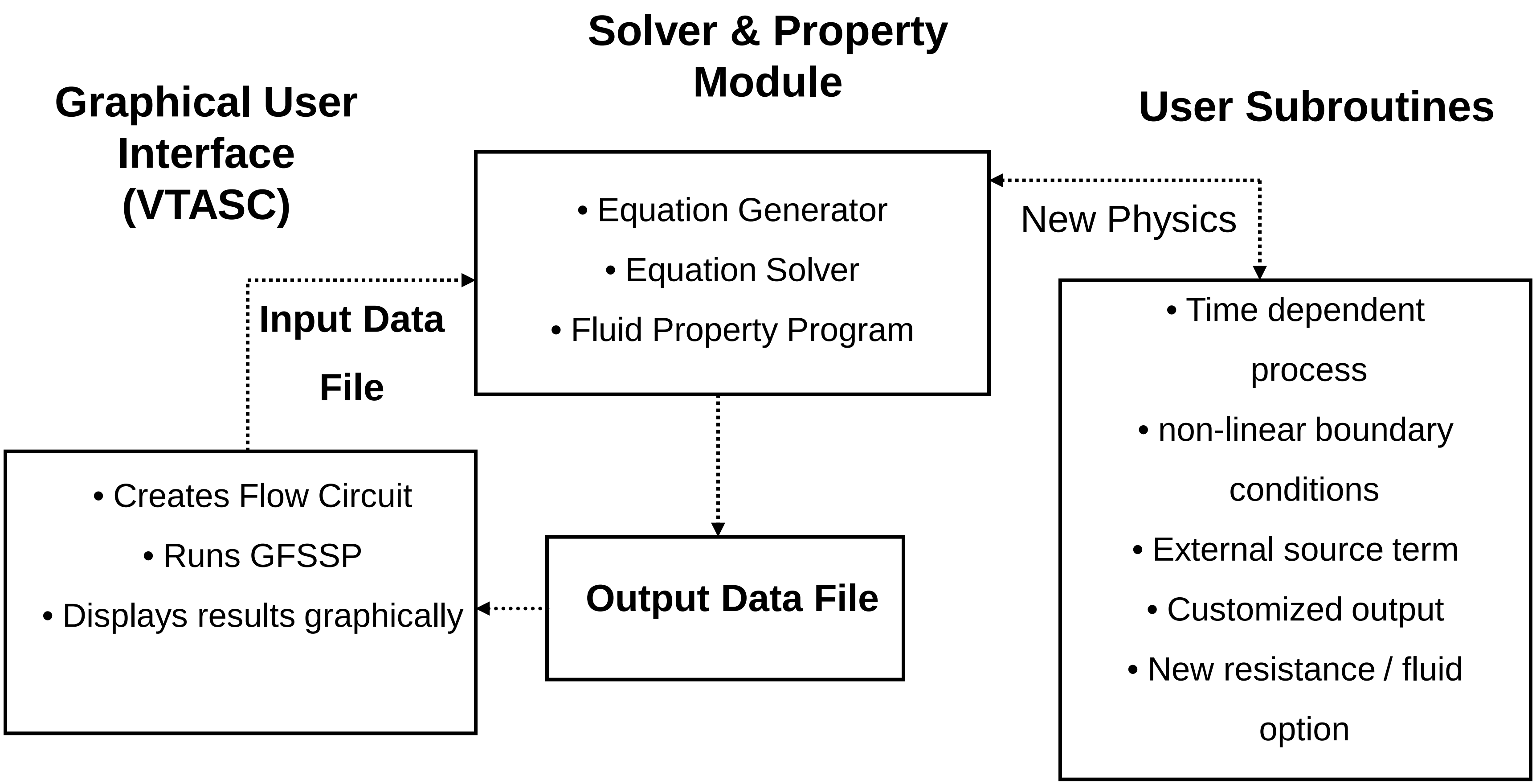
- Version 1.4 (Steady State) was released in 1996
- Version 2.01 (Thermodynamic Transient) was released in 1998
- Version 3.0 (User Subroutine) was released in 1999
- Graphical User Interface, VTASC was developed in 2000
- Selected for NASA Software of the Year Award in 2001
- Version 4.0 (Fluid Transient 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.

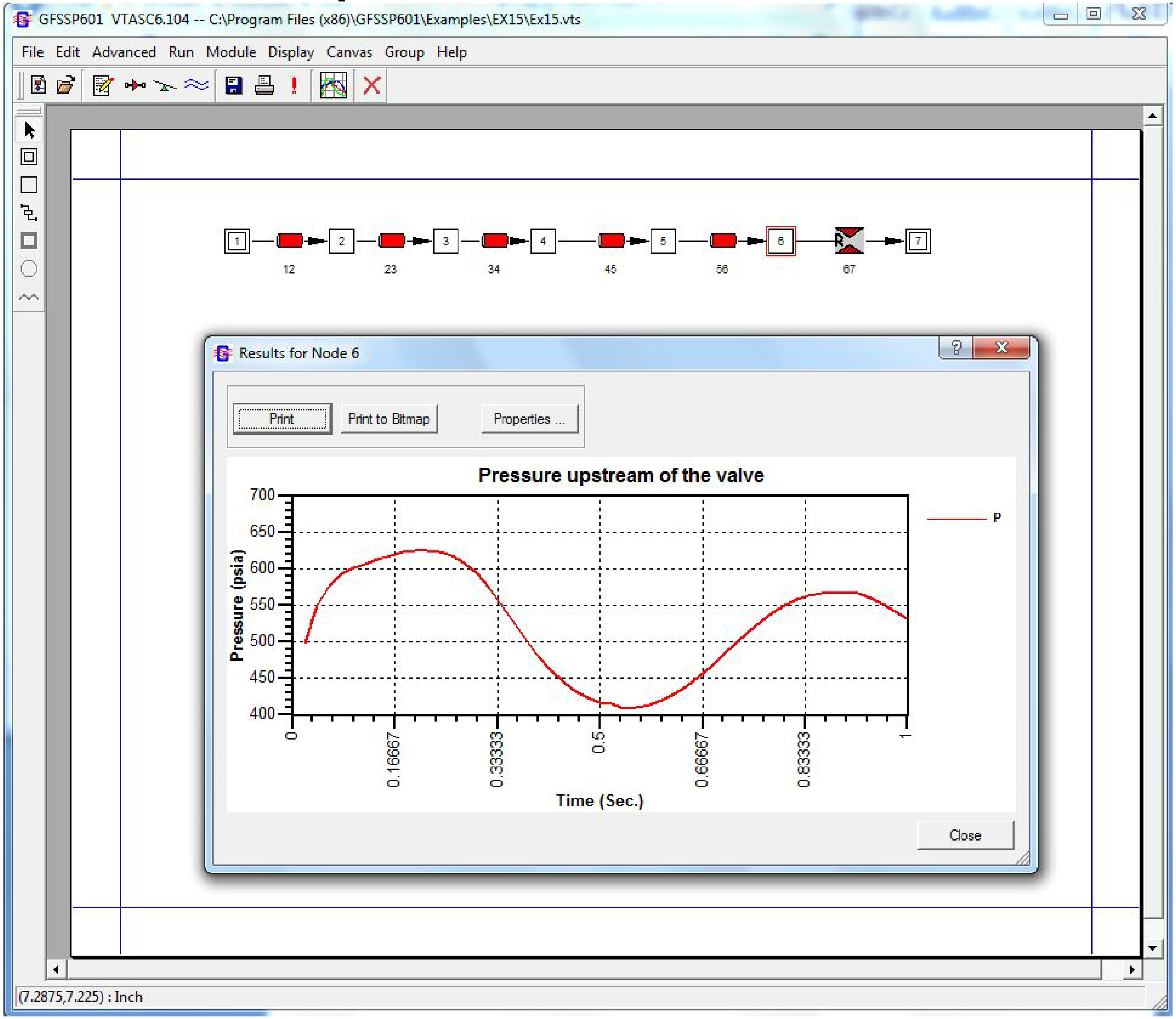
Program Structure



Mathematical Closure

Unknown Variables	**Available Equations to Solve**
1. Pressure	1. Mass Conservation Equation
2. Flowrate	2. Momentum Conservation Equation
3. Fluid Temperature	3. Energy Conservation Equation of Fluid
4. Solid Temperature	4. Energy Conservation Equation of Solid
5. Specie Concentrations	5. Conservation Equations for Mass Fraction of Species
6. Mass	6. Thermodynamic Equation of State

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

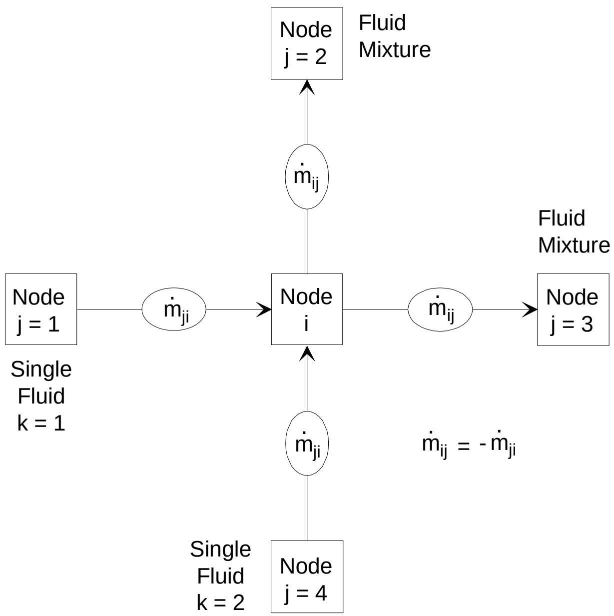
Fluid Mixture Option with Phase Change

- 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

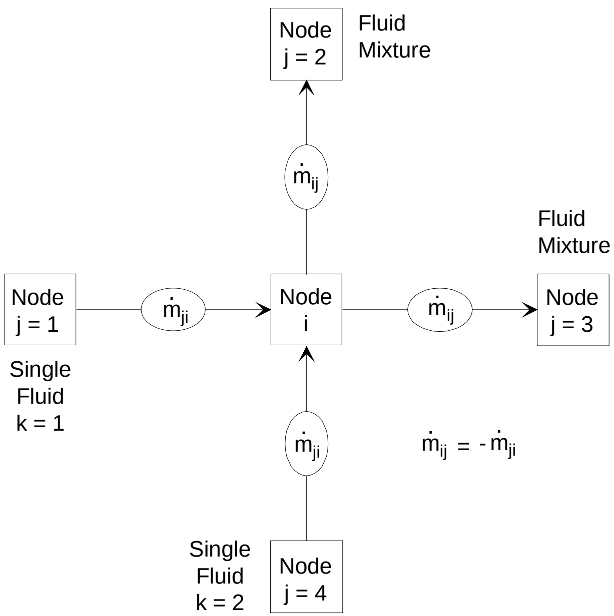
$$h_{i,\tau+\Delta\tau} = \frac{\sum_{j=1}^{j=n}\sum_{k=1}^{k=n_f} x_{j,k} h_{j,k} MAX\left[-\dot{m}_{ij}, 0\right] + \frac{(mh_i)_\tau}{\Delta\tau} + \dot{Q}_i}{\sum_{j=1}^{j=n}\sum_{k=1}^{k=n_f} x_{j,k} MAX\left[\dot{m}_{ij}, 0\right] + \frac{m_\tau}{\Delta\tau}}$$

Temperature Equation

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

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



$$\frac{\left(m_i h_{ik} - \frac{p}{\rho_k J}\right)_{\tau+\Delta\tau} - \left(m_i h_{ik} - \frac{p}{\rho_k J}\right)_{\tau}}{\Delta\tau}$$

Transient Term

$$= \sum_{j=1}^{j=n} \left\{ MAX\left[-\dot{m}_{ij}, 0\right] h_{jk} - MAX\left[\dot{m}_{ij}, 0\right] h_{ik} \right\} + \dot{Q}_{ik} + \left\{ \pm \dot{Q}^{HES}_{1\rightarrow 2} \right\}$$

Advection Term *Source Term*

Thermodynamic Properties

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

$$T_{ik} = f(p_i, h_{ik})$$
$$\rho_{ik} = f(p_i, h_{ik})$$
$$\mu_{ik} = f(p_i, h_{ik})$$
$$K_{ik} = f(p_i, h_{ik})$$
$$C_{p_{ik}} = f(p_i, h_{ik})$$

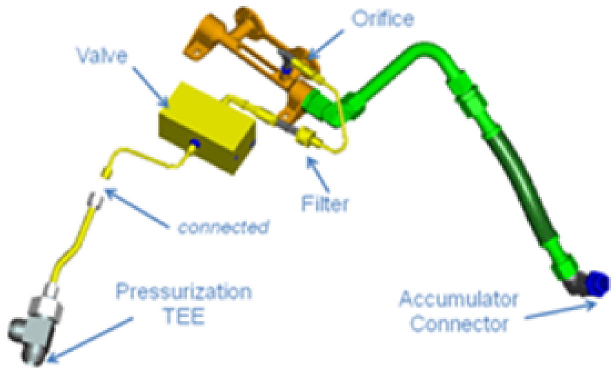
- The nodal properties are calculated by averaging the properties of species:

$$\rho_i = \sum_{k=1}^{n_f} \bar{c}_{ik}\, \rho_{ik}$$

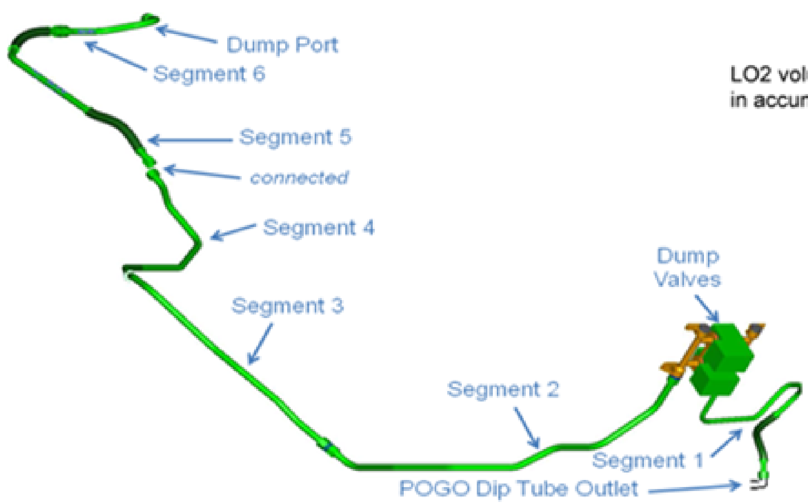
$$\mu_i = \sum_{k=1}^{n_f} \bar{c}_{ik}\, \mu_{ik}$$

- 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

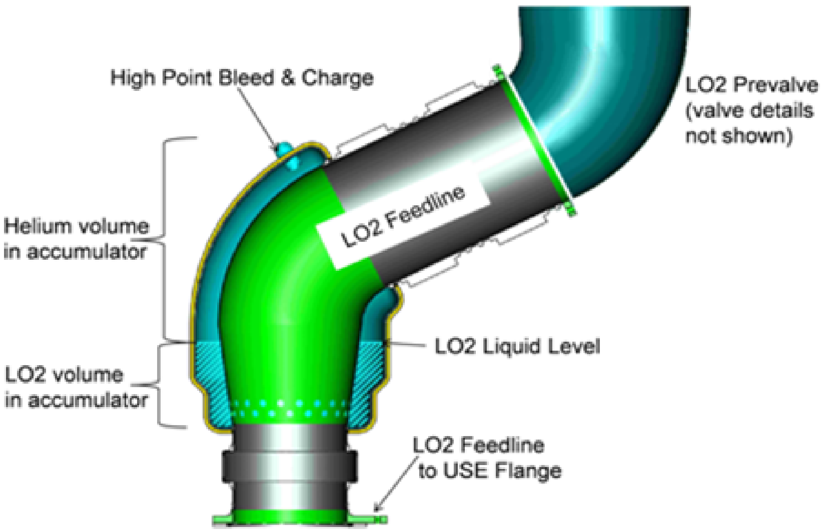
Pogo Accumulator with Charge Line and Dump line



Charge System

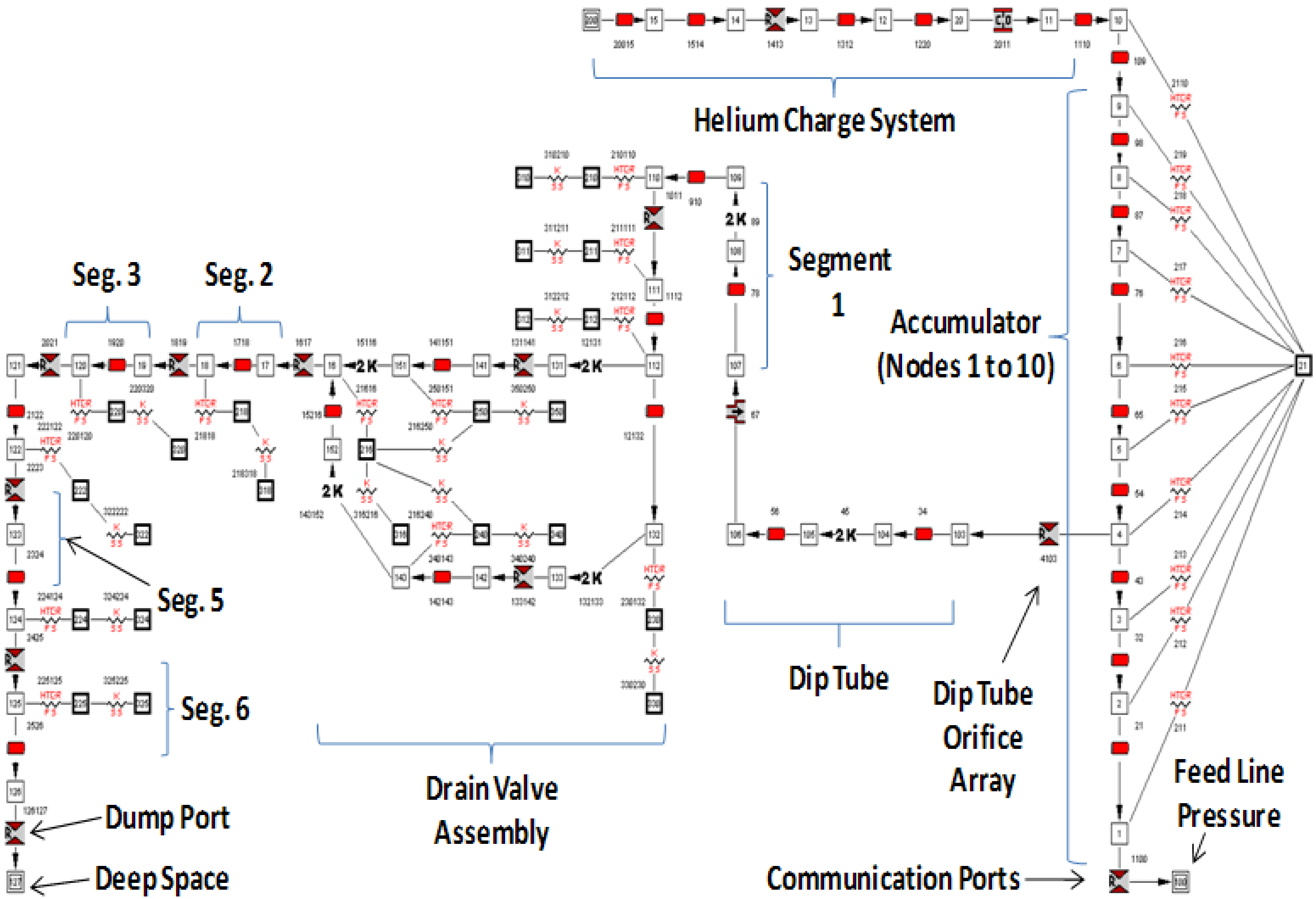


Dump System

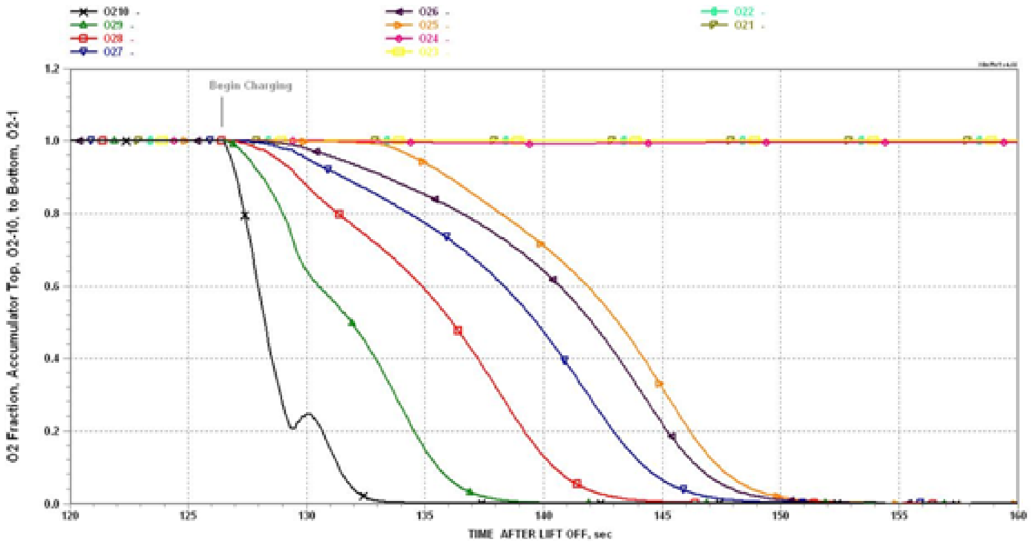


POGO Accumulator wrapped around LO2 Feed Line

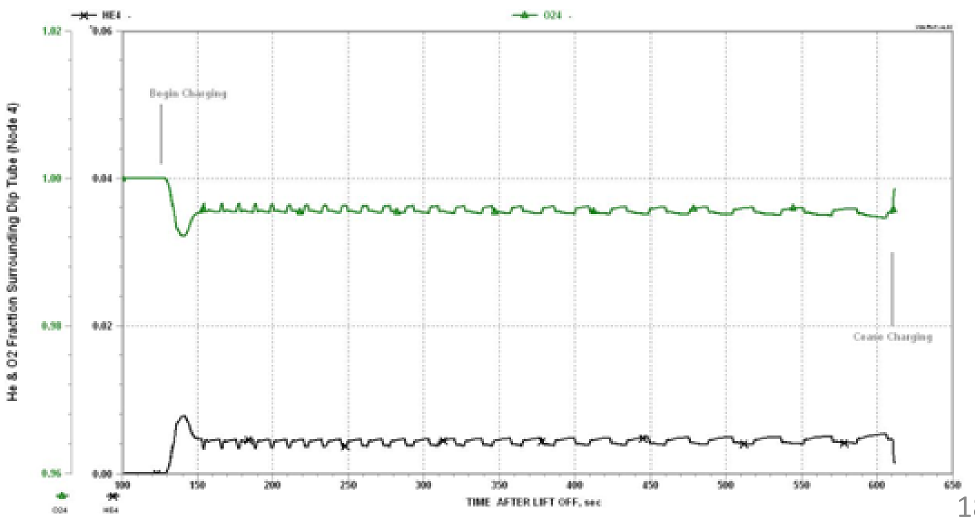
GFSSP Model of Pogo Accumulator & Drain Line



Charging of helium & draining of He-LO2 mixture



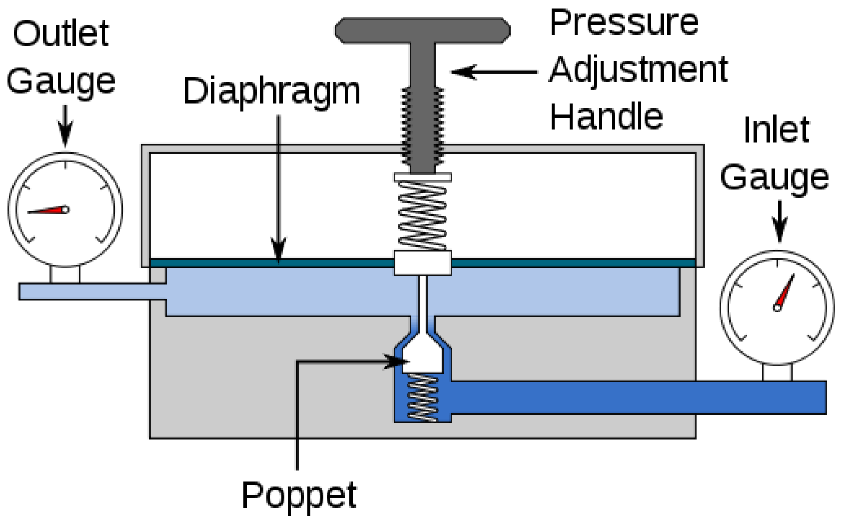
Displacement of Oxygen from the Accumulator during charging



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 & Forward Differencing Algorithm

$$A_{new} = A_\tau - \frac{\partial A}{\partial p}\left(p_\tau - p_{reg}\right)$$

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

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

<u>Backward Differencing Scheme</u>

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

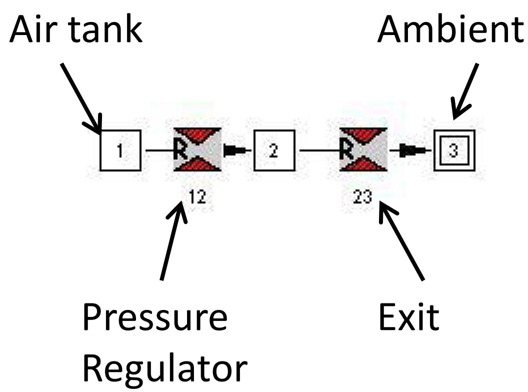
where,

$$A_{new} = A_\tau \left(\frac{p_{reg}}{p_\tau}\right)^3 \left(e^{\left(\frac{p_{reg}}{p_\tau} - 1\right)}\right),$$

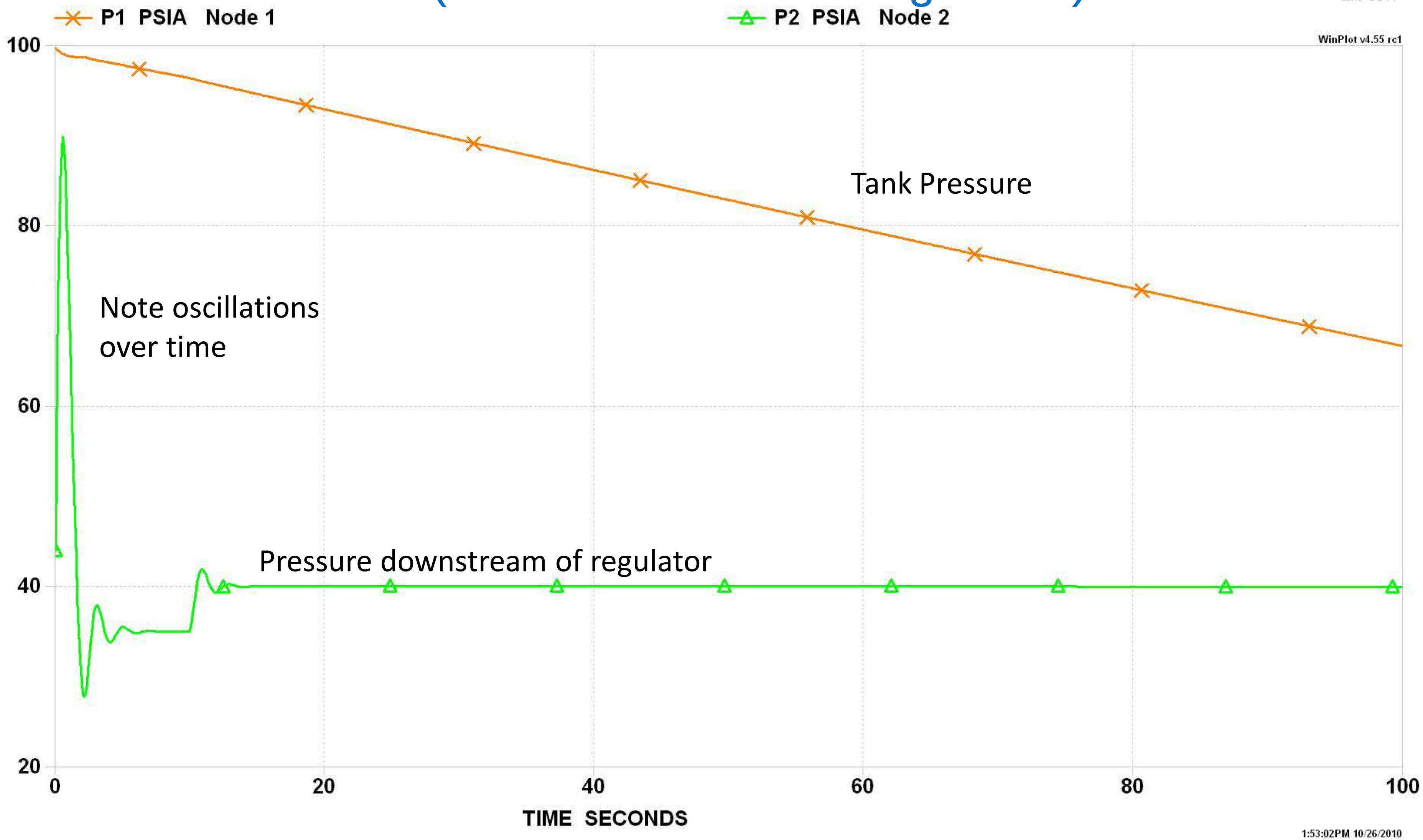
<u>Forward Differencing Scheme</u>

Application of Forward Looking Algorithm

Reference: Forward Looking Pressure Regulator Algorithm for Improved Modeling Performance with the Generalized Fluid System Simulation Program by Paul Schallhorn & Neal Hass, AIAA Paper No. 2004-3667



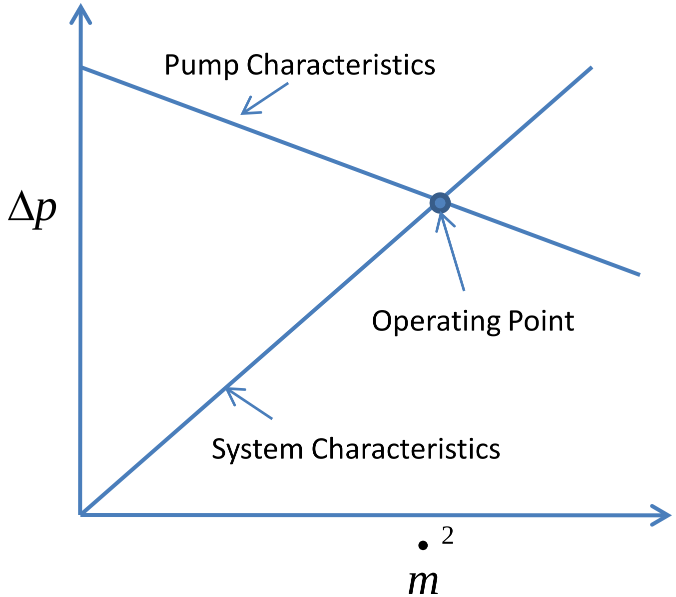
Pressure History
(Schallhorn & Haas Algorithm)

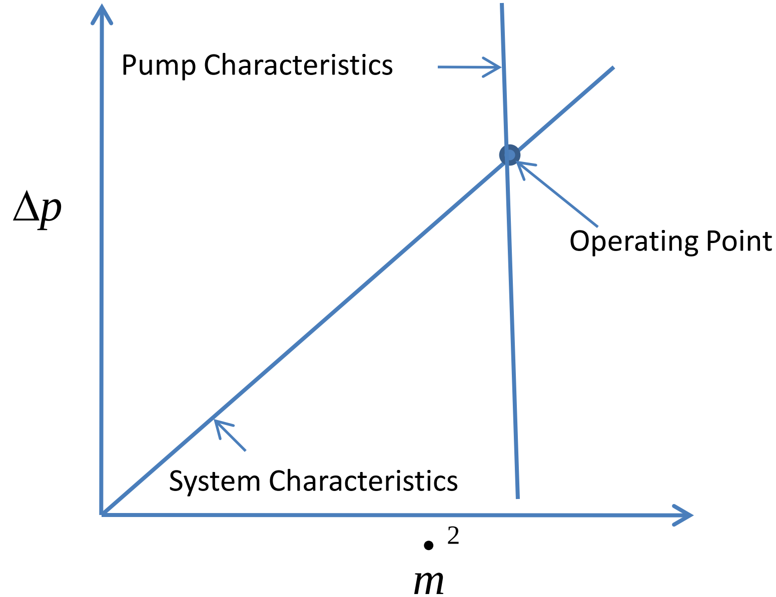


Fixed Flow Option

- 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)

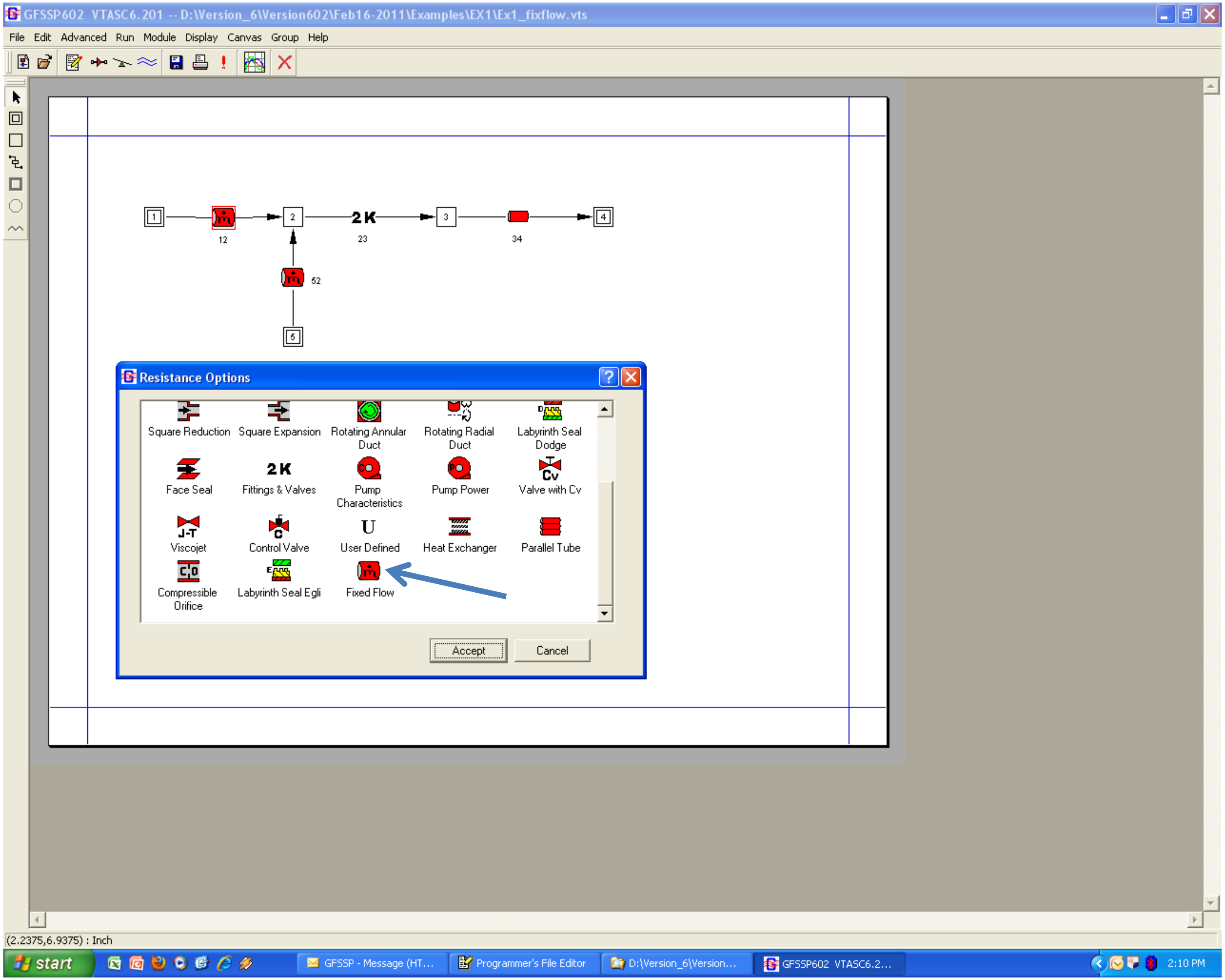




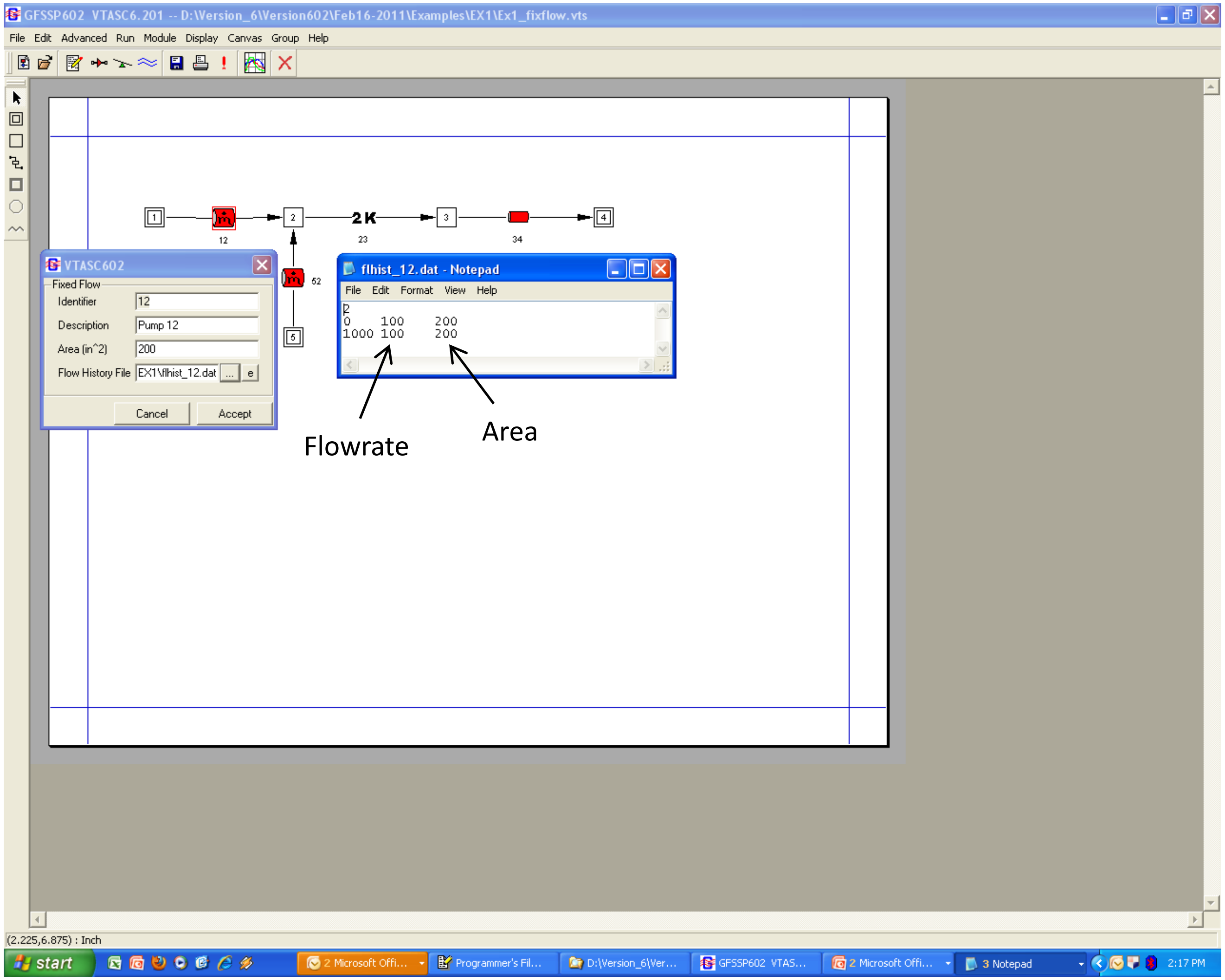
$$\Delta p = A + C\,\dot{m}\left|\dot{m}\right| \quad \text{where } A = \alpha\,\dot{m}\left|\dot{m}\right| \;;\; C = -\alpha; where\;\; \alpha = 1\times10^{25}$$

$$\text{Substituting A and C , one gets: } \dot{m} = \frac{\dot{m}\left|\dot{m}\right|}{\left|\dot{m}\right|}$$

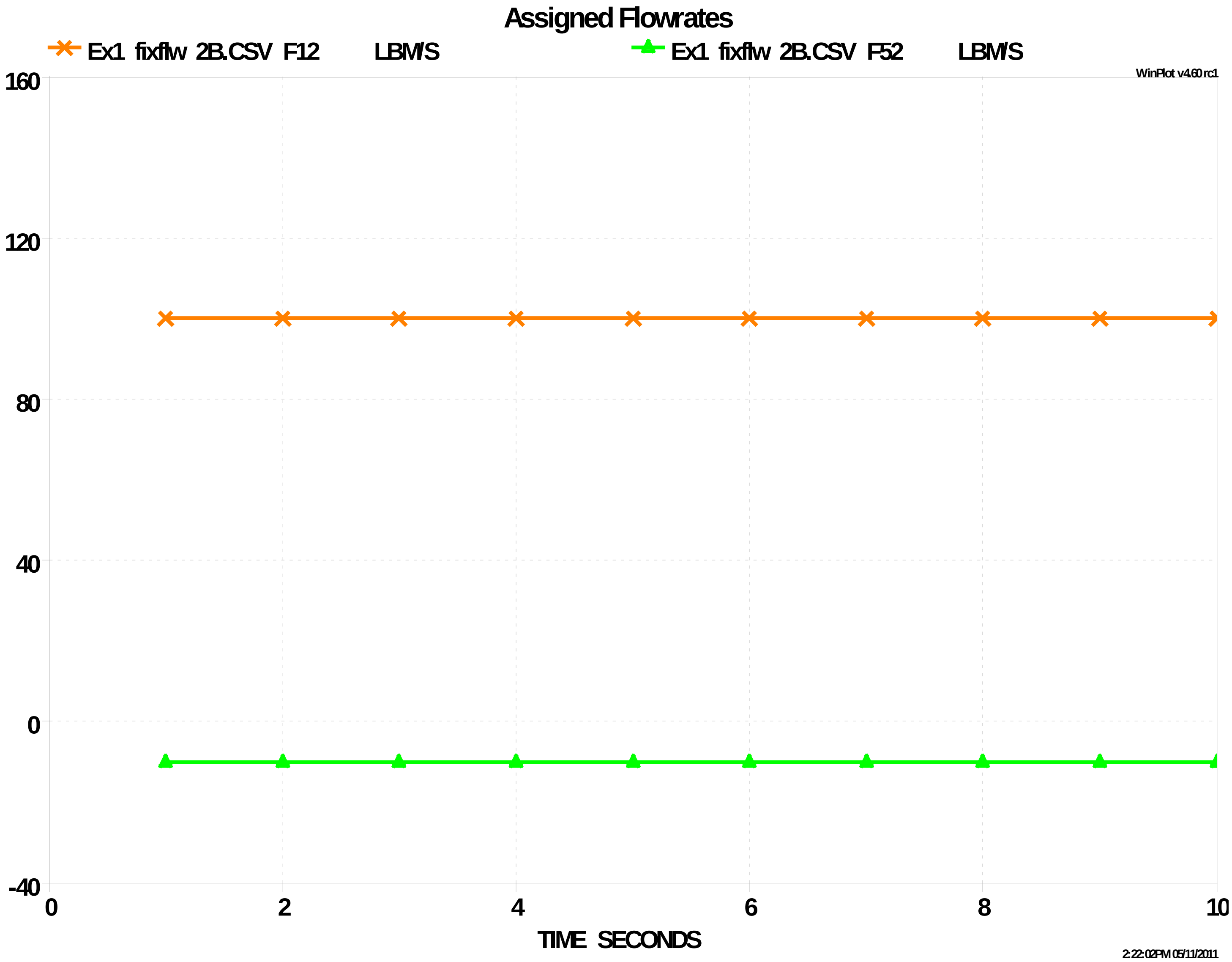
New Resistance Option – Fixed Flow



Properties of Fixed Flow Option

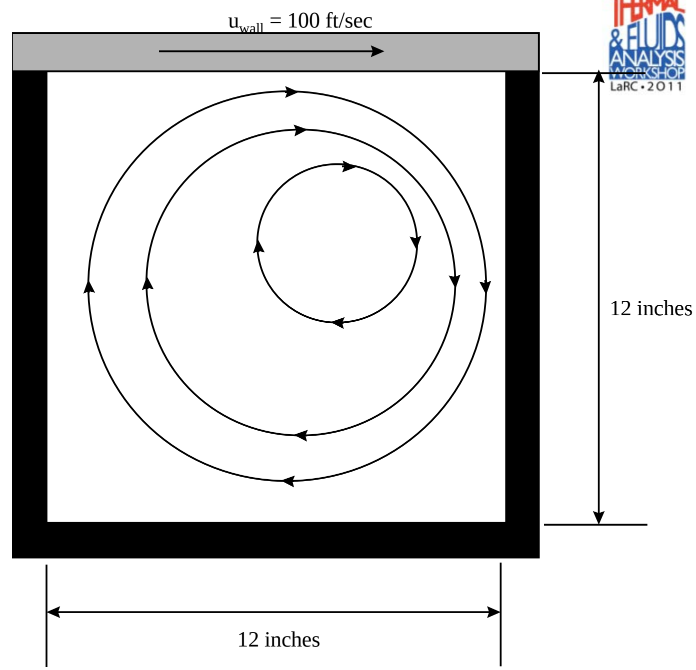


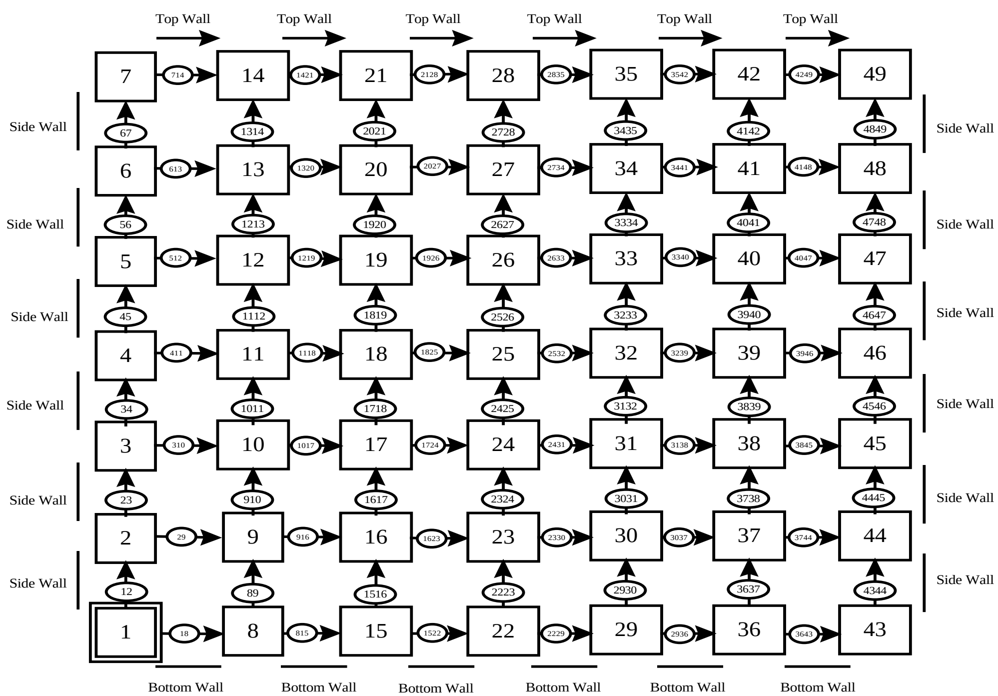
Results of Fixed Flow Option

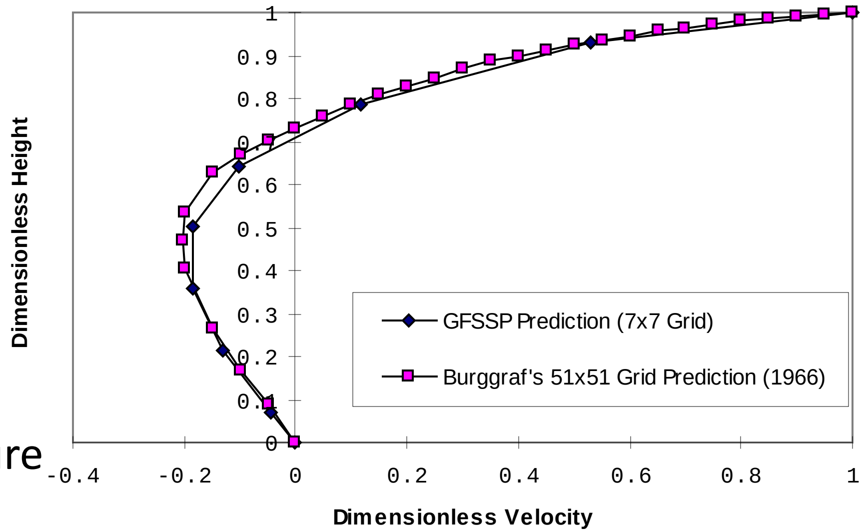


Two-dimensional Navier-Stokes Solver

- 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

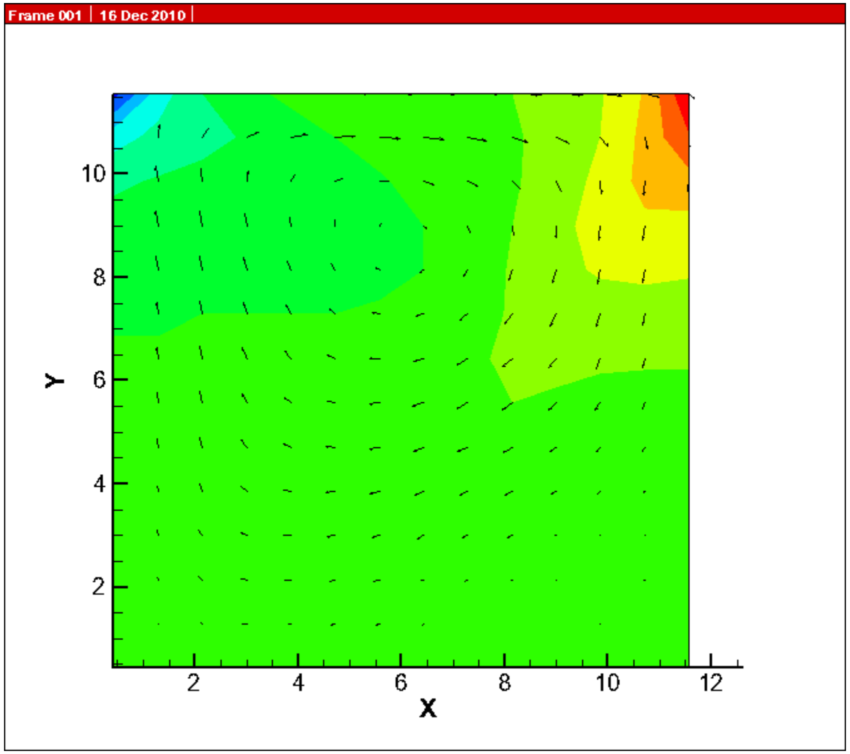




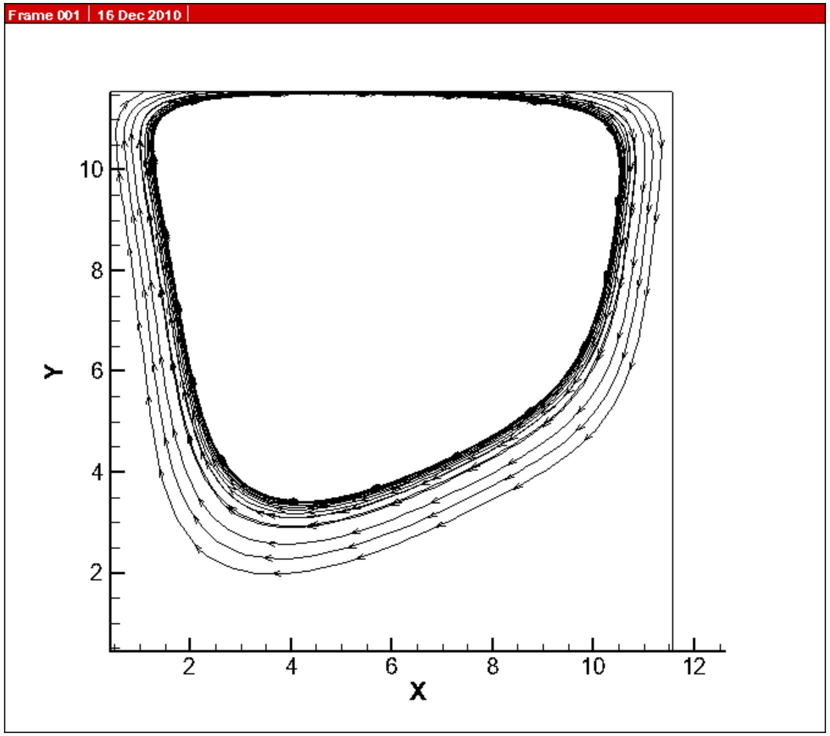


Shear Driven Square Cavity Centerline Velocity Distribution

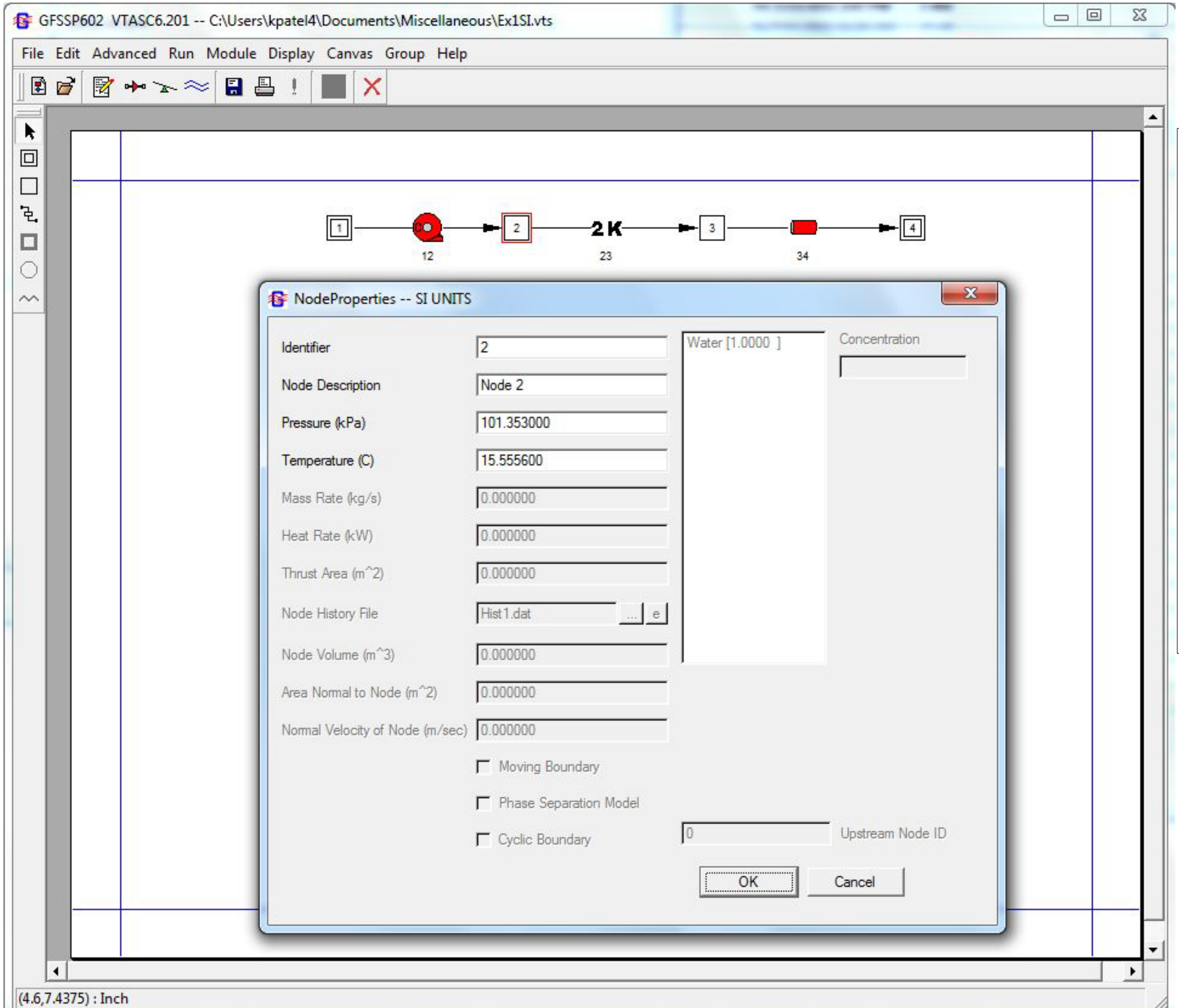
Velocity Field and Pressure Contours



Predicted Stream Traces



S I 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

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