RELAP5-3D Compressor Model

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Compressor characteristics

- *Positive Displacement*
  - *Low flow rates, high pressure ratio*
- *Dynamic*
  - *Convert velocity to pressure in continuous flow process*
  - *Centrifugal*
    - $1.3 < P_o/P_i < 13$
    - $75\% < \eta < 87\%$
  - *Axial flow*
    - $1.1 < P_o/P_i < 1.4$
    - $80\% < \eta < 91\%$

Centrifugal Compressor

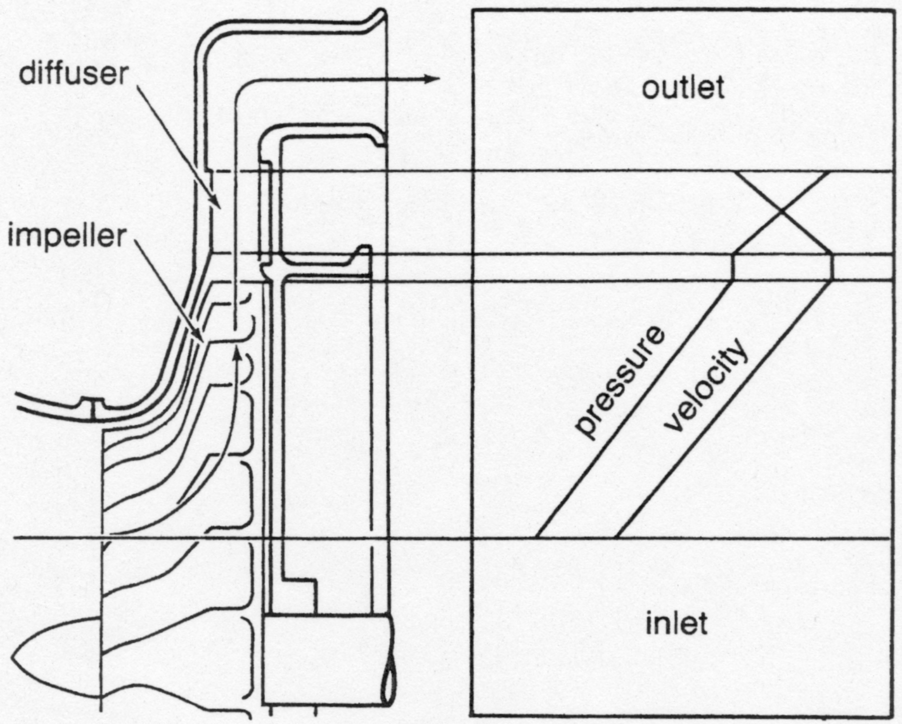
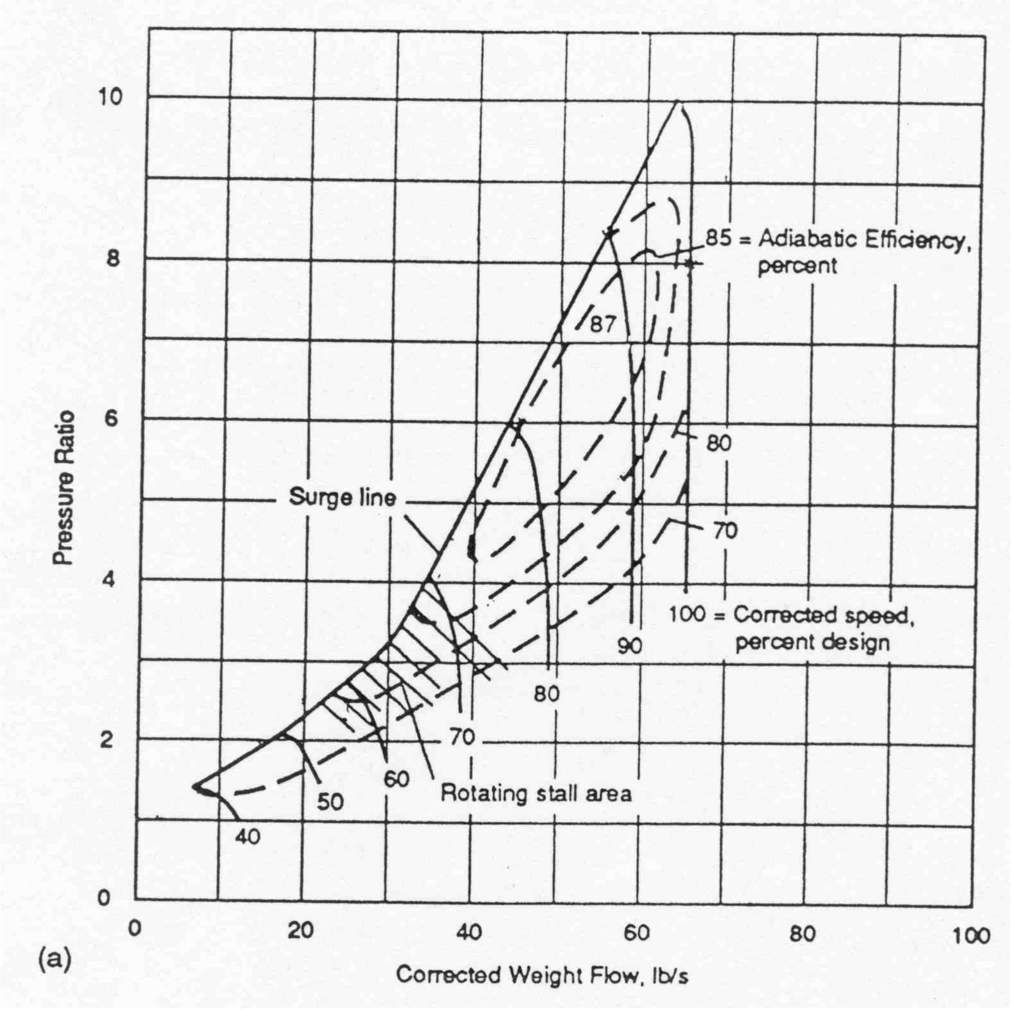


Figure 6-1. Pressure and velocity through a centrifugal compressor.

Centrifugal Compressor Performance Characteristics



Axial Flow Compressor

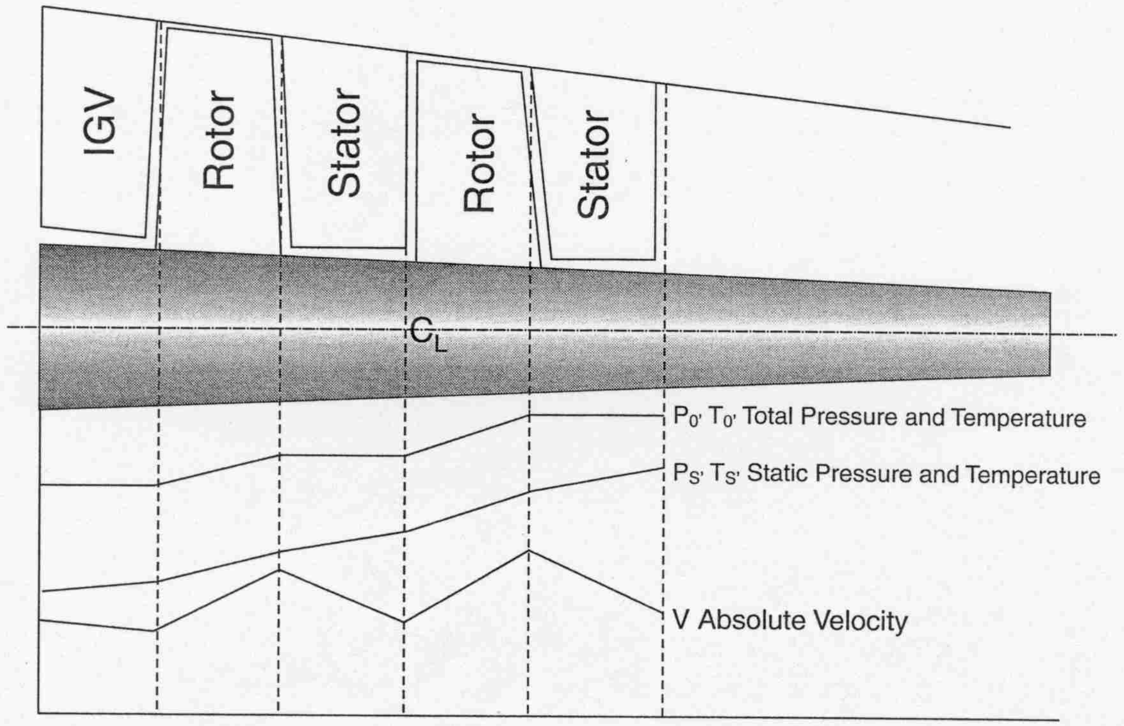
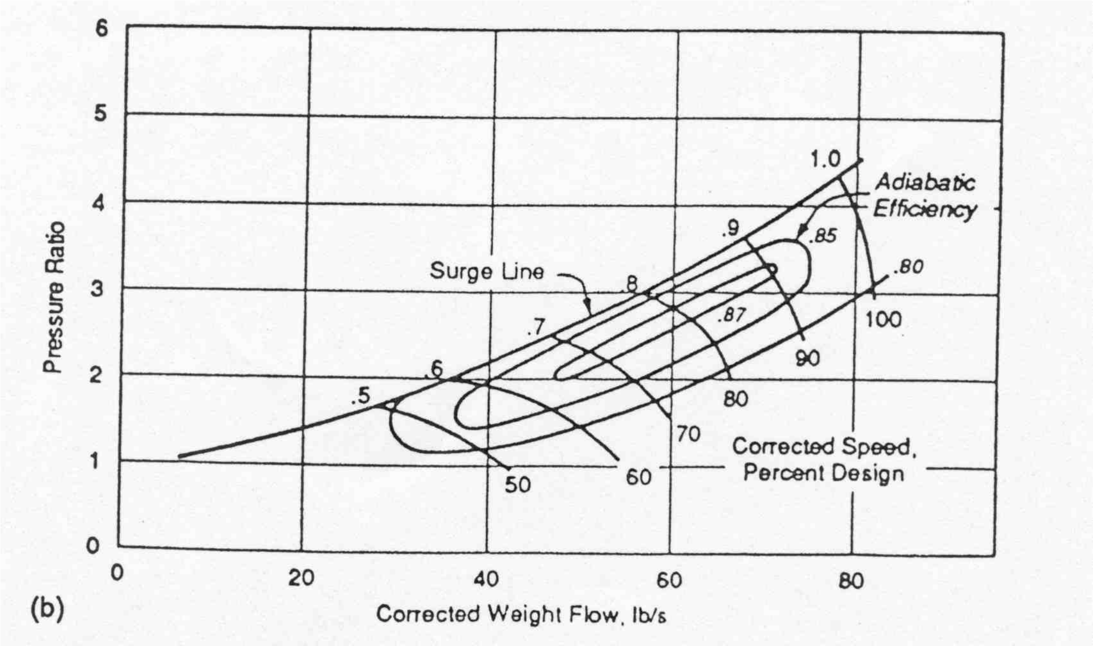
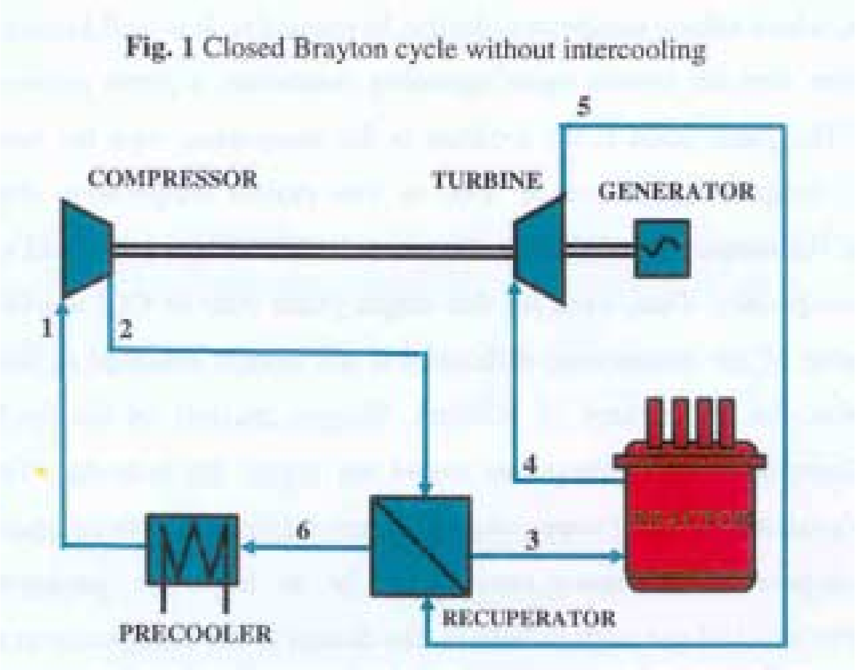


Figure 7-3. Variation of enthalpy, velocity, and pressure through an axial-flow compressor.

Axial Flow Compressor Performance Characteristics

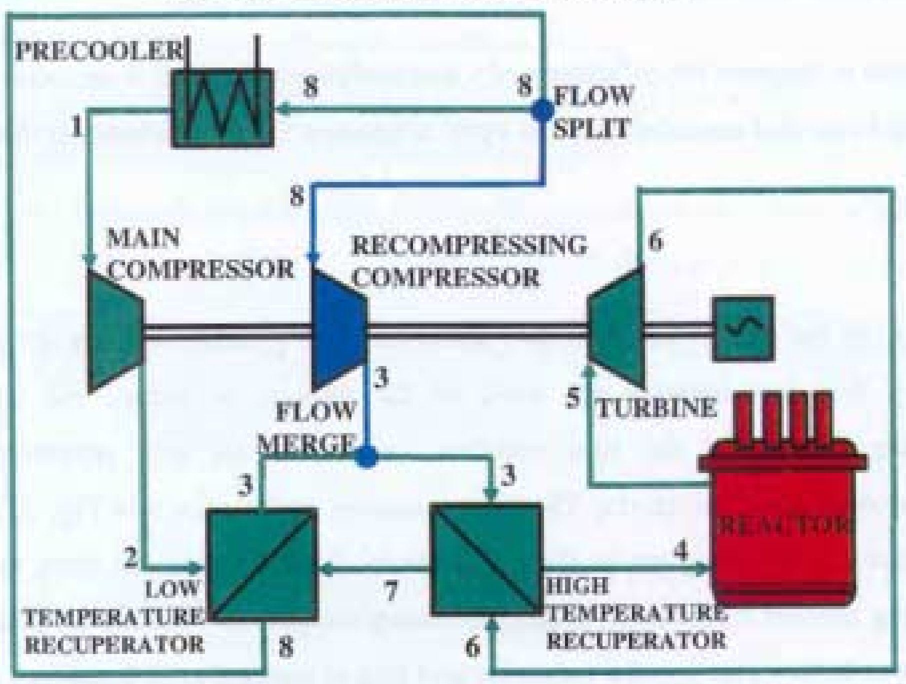


Simple Brayton Cycle Reactor



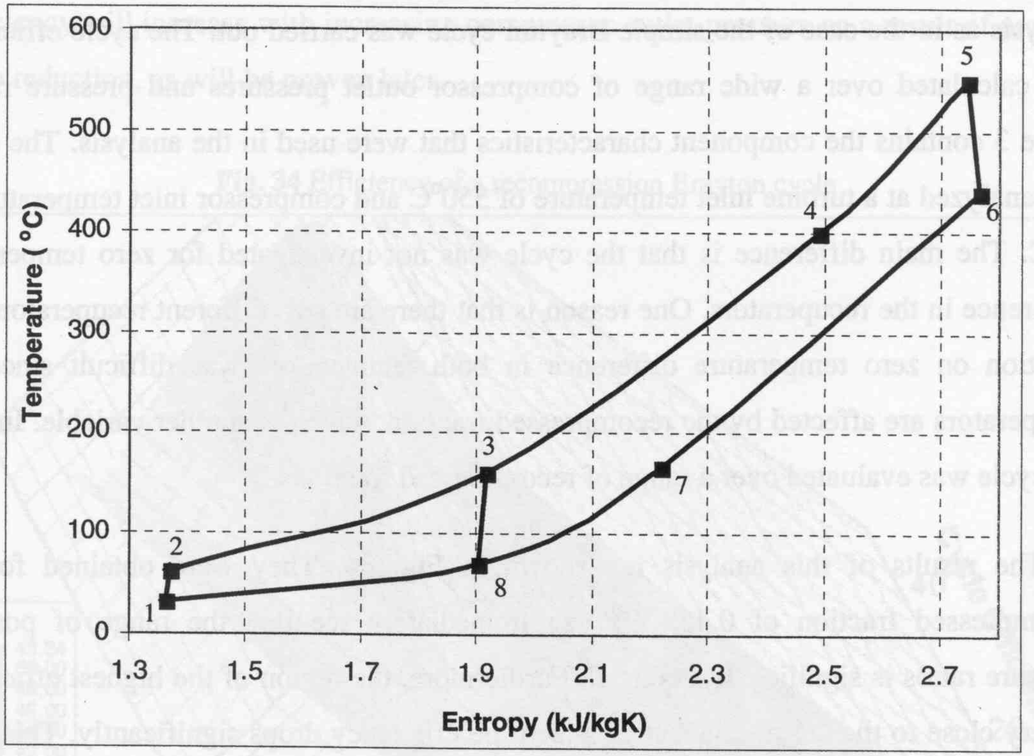
Recompression Brayton Cycle Reactor

Fig. 32 Recompression Brayton cycle layout



Recompression Brayton Cycle Diagram

Fig. 33 Temperature-entropy diagram of a recompression Brayton cycle



A compressor is similar to a pump

- *Rotational Velocity*
  - *Input from table with or without trip*
  - *Torque-Inertia equation, optionally with motor torque*
  - *Shaft rotational velocity equation*
- *Spindown (coastdown) Data*
- *Dissipation*
- *Rotor Inertia*
- *Configuration differences*
  - *Inlet junction has head added to fluid*
  - *Volume is outlet state*
  - *Optional outlet junction*
  - *Outlet can be connected to another compressor or a non-compressor*

Performance Characteristics

- *Normal Operation*
  - *Region between the surge and choke points*
  - *Surge*
    - *aerodynamic instability in impeller or diffuser*
    - *intermittent flow direction (and force direction) reversal*
  - *Choking*
    - *sonic flow at minimum area point*
    - *efficiency drops rapidly*
- *Reverse flow*
  - *Turbine*
  - *Further investigation pending development of design information*
- *Reverse direction*
  - *Further investigation pending development of design information*

Compressor H-S Diagram

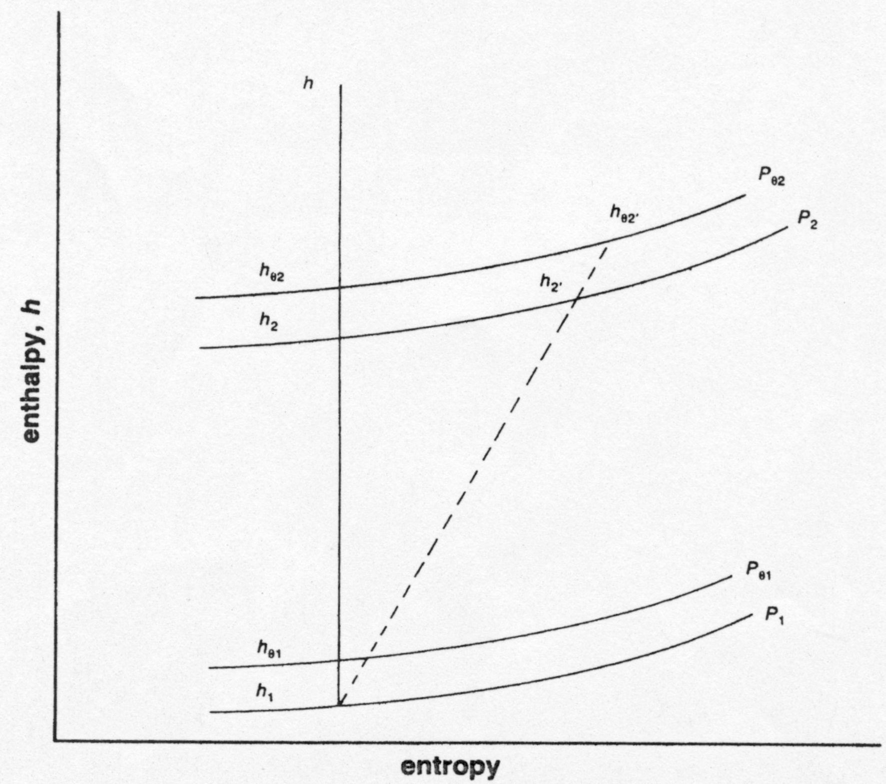


Figure 3-4. Entropy-enthalpy diagram of a compressor.

A change in angular momentum of working fluid is caused by tangential forces (only). Isentropic torque can be calculated by considering an isentropic compression of the fluid ...

$$\tau = \dot{m}\,(r_1 \cdot V_{\theta 1} - r_2 \cdot V_{\theta 2}) \qquad (1)$$

$$\tau \cdot \omega = \dot{m}\,(r_1 \cdot \omega \cdot V_{\theta 1} - r_2 \cdot \omega \cdot V_{\theta 2}) \qquad (2)$$

$$\dot{Q}_{c.v.} + \dot{m}\left(h_1 + \frac{V_1^{\,2}}{2 \cdot g_c} + Z_1 \frac{g}{g_c}\right) = \dot{m}\left(h_2 + \frac{V_2^{\,2}}{2 \cdot g_c} + Z_2 \frac{g}{g_c}\right) + \dot{W}_{c.v.} \qquad (3)$$

$$\dot{W}_{c.v.} = \tau_s \cdot \omega = \dot{m}\left(h_1^T - h_2^T\right) \qquad (4)$$

$$s_1 = s\left(h_1^T, \rho_1\right) \qquad (5)$$

The work in the azimuthal direction (only) is isentropic, so an isentropic outlet state can be defined.

$$R_P = R_P(\omega, \dot{m}) = \frac{P_2^T}{P_1^T} \quad (6)$$

$$P_2^T = P_1^T \cdot R_P \quad (7)$$

$$s_2 = s_1 \quad (8)$$

$$h_2^T = h\,(P_2^T, s_2) \quad (9)$$

$$\rho_2 = \rho\left(P_2^T, s_2\right) \quad (10)$$

Real outlet state is then obtained from definition of efficiency.

$$\tau_s = \frac{\dot{m}}{\omega}\left(h_2^T - h_1^T\right) \tag{11}$$

$$\eta_{ad} = \frac{Isentropic\ work}{Actual\ work} = \frac{h_2^T - h_1^T}{h_{2'}^T - h_1^T}, \tag{12}$$

$$h_{2'}^T = \frac{h_2^T - (1-\eta_{ad})\cdot h_1^T}{\eta_{ad}} \tag{13}$$

$$\tau_d = \frac{\dot{m}}{\omega}\frac{1-\eta}{\eta}\left(h_2^T - h_1^T\right). \tag{14}$$

$$\dot{W}_d = \tau_d \cdot \omega \tag{15}$$

If assumption is made about outlet state, actual work done on the fluid can be calculated without entropy-based property table lookup call.

$$\int_{P_1}^{P_2} \frac{dP}{\rho} + \frac{V_2^2 - V_1^2}{2} = g \cdot H \,, \qquad \text{Assume:} \quad \rho_m = \frac{\rho_1 + \rho_2}{2} \qquad (16)$$

$$P_2 + \frac{\rho_m V_2^2}{2} = P_1 + \frac{\rho_m V_1^2}{2} + \rho_m \cdot g \cdot H \qquad (17)$$

$$P_2^T = P_1^T + \rho_m \cdot g \cdot H = P_1^T + P_1^T (R_P - 1) \qquad (18)$$

$$\Delta P = \rho_m \cdot g \cdot h = P_1^T (R_P - 1) = P_2^T \left(\frac{R_P - 1}{R_P}\right) \qquad (19)$$

Use efficiency to separate isentropic and dissipative components of torque.

$$\dot{W}_{c.v.} = \dot{m}\,(h_{2'}^{T} - h_{1}^{T}) = \dot{m}\,(h_{2}^{T} - h_{1}^{T}) + \dot{m}\,(h_{2'}^{T} - h_{2}^{T}) = \dot{W}_{s} + \dot{W}_{d} \qquad (20)$$

$$\dot{W}_{s} = \dot{m} \cdot g \cdot H = \frac{\dot{m} \cdot \Delta P}{\rho_{m}}. \qquad (21)$$

$$\tau_{s} = \frac{\dot{m}}{\omega}\left(h_{2}^{T} - h_{1}^{T}\right) = \frac{\dot{m}}{\omega}\frac{\Delta P}{\rho_{m}} \qquad (22)$$

$$\tau_{d} = \frac{\dot{m}}{\omega}\frac{1-\eta}{\eta}\left(h_{2}^{T} - h_{1}^{T}\right) = \frac{\dot{m}}{\omega}\frac{1-\eta}{\eta}\frac{\Delta P}{\rho_{m}} \qquad (23)$$

Head and Torque Calculation Summary

- *Isentropic torque can be derived using first principles*
  - *Pressure ratio and inlet entropy determine isentropic outlet state*
  - *Efficiency determines real outlet state and dissipative torque*
- *RELAP5-3D implementation*
  - *Pressure Ratio, linearized density used to calculate real outlet state*
  - *Hand calculations verify the accuracy of linearized density assumption*
  - *Efficiency determines isentropic and dissipative torque components*
- *Dissipative torque added to energy eqn*

Performance Data Issues

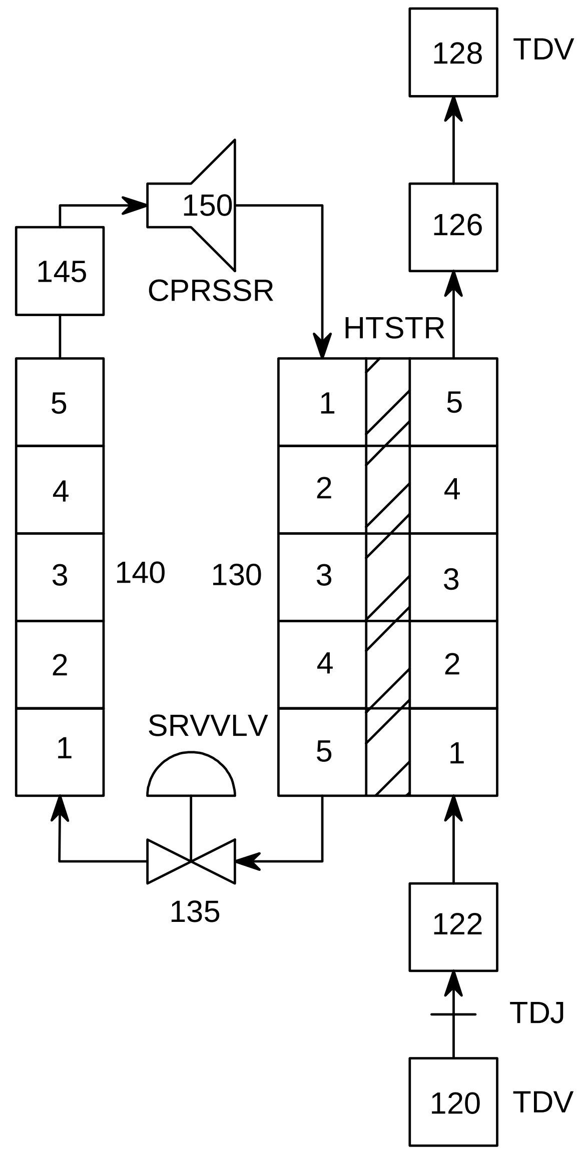
- Surge line limit
  - startup
  - transient response
  - input from designers
  - gain experience with test problem
- Reverse flow, reverse direction, spin-down
  - input from designers
  - Incorporate capability for input

Implementation Status

- *Input processing (rlevel) and cross checking (ilevel) completed*
- *Compressor model completed with momentum and dissipation terms in semi-explicit method*
- *Test model built*
  - *Simple loop with compressor, heat exchanger, orifice*
  - *Performance data from automobile turbocharger compressor*
  - *Extrapolation and mesh refinement to provide necessary numbers*
- *Component variables added to rstplt file*
  - *Cprvel, cprhead, cprtrq, cpreff, cprmt, cprnrt*

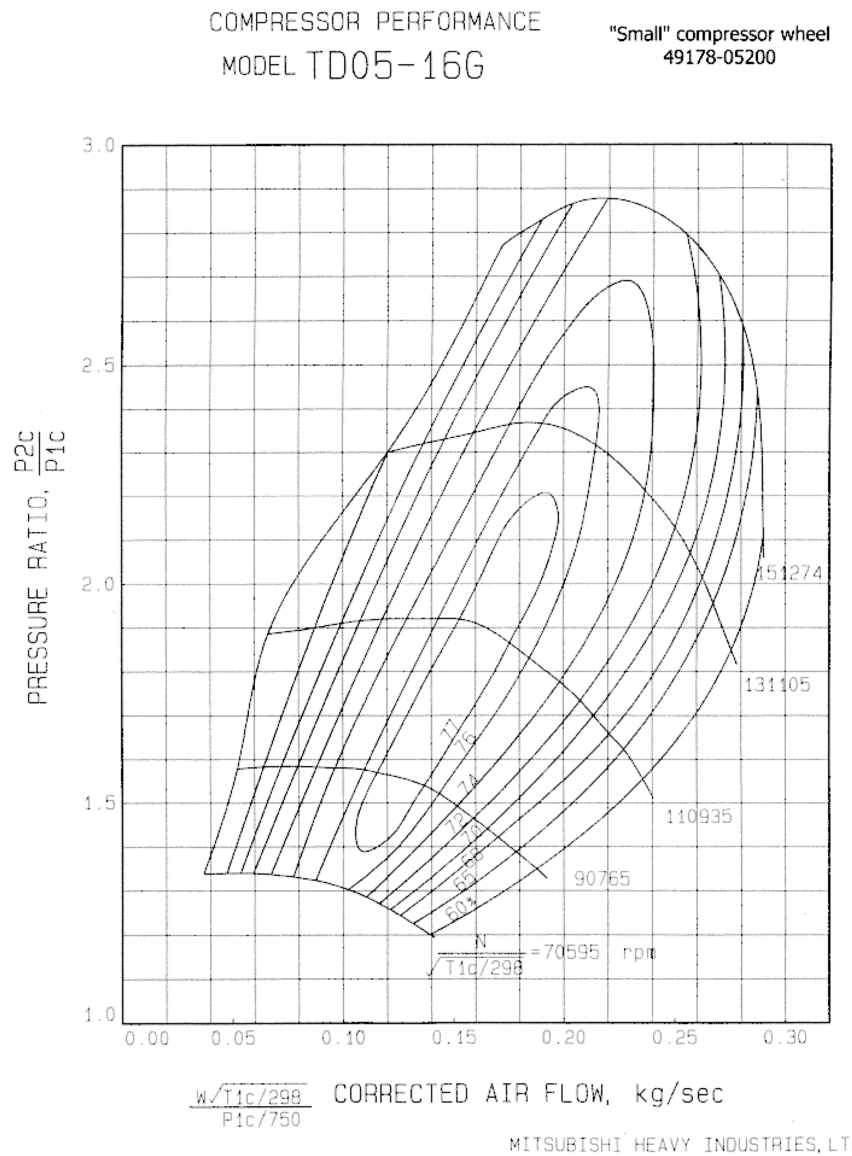
Test Input File

- *Simple loop with heat removal*
- *Working fluid is air at atmospheric pressure*
- *SRVVLV component fully open*
- *Wall Friction in Pipe 140*
- *Calculations*
  - *Ramp from zero to rated speed*
  - *Steady state at rated speed*

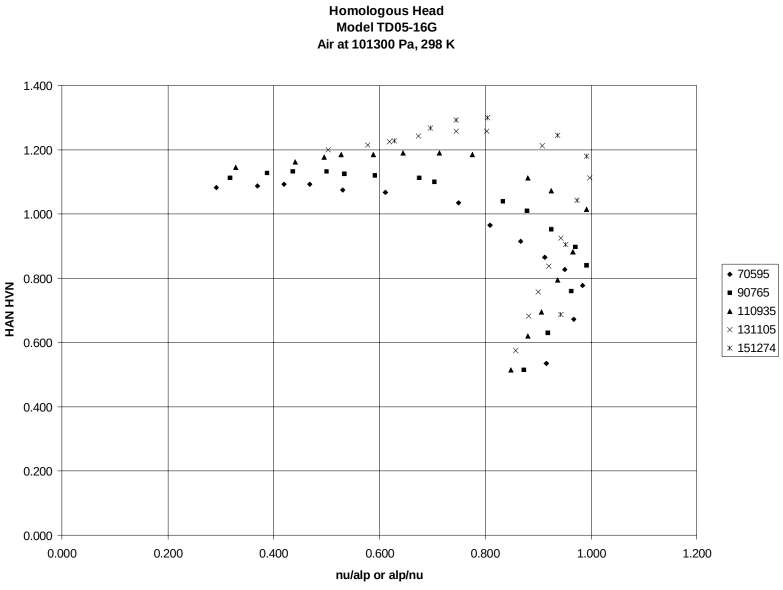


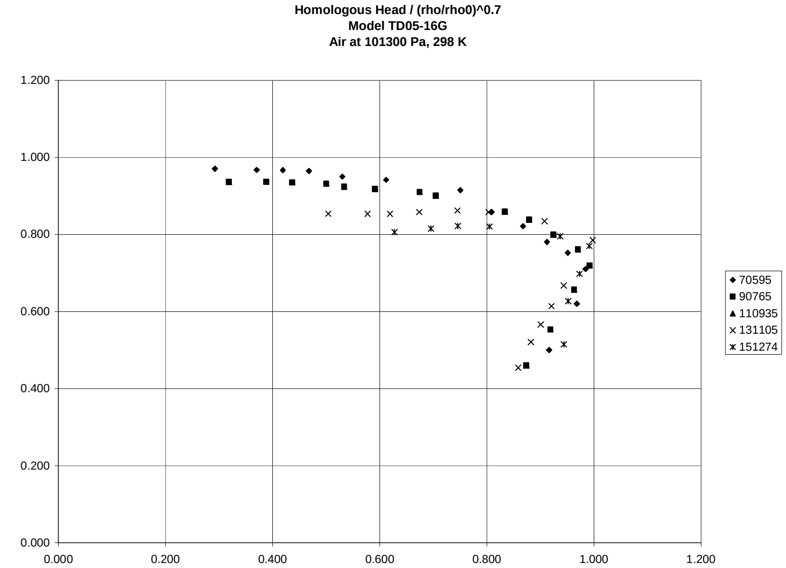
Automobile Turbocharger Compressor

- *Centrifugal Compressor*
- *Air as working fluid*
- *Data digitized*
- *Homologous form*



Homologous Representation of Data (air at atomspheric conditions)

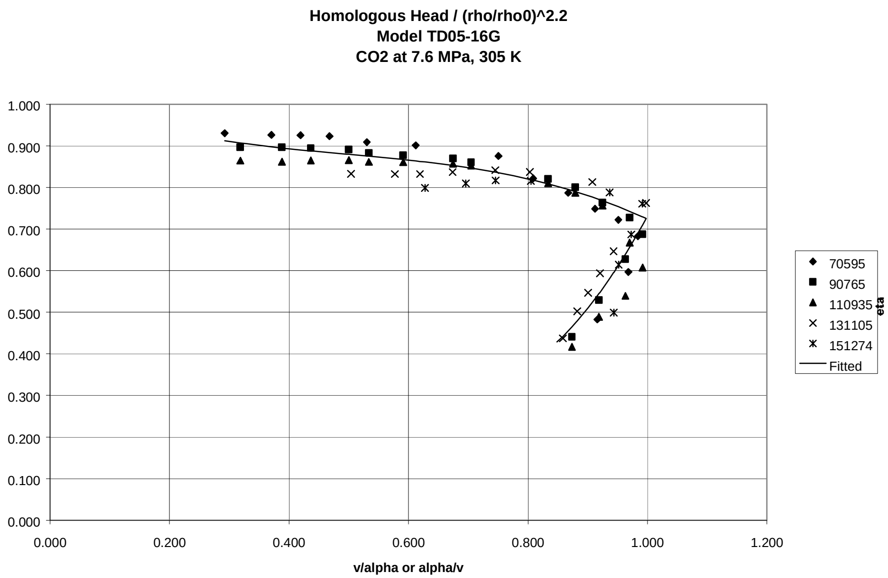




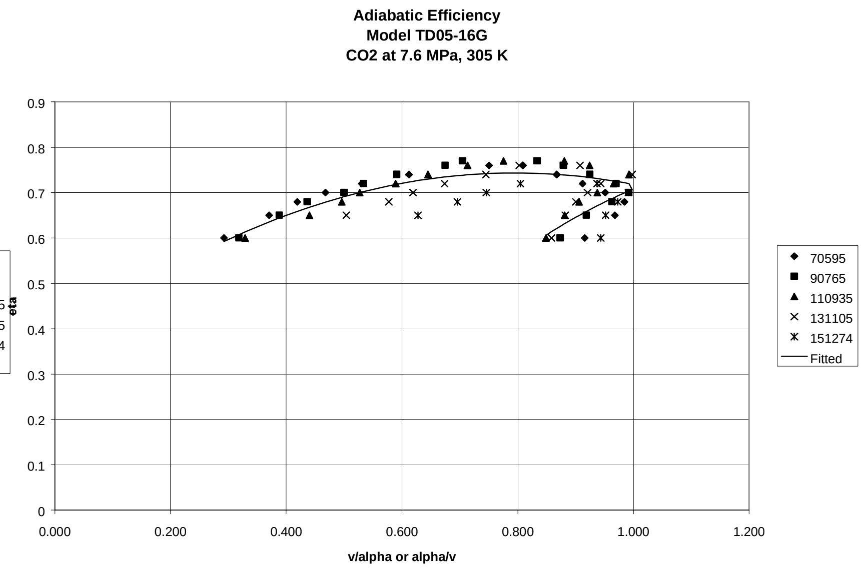
Uncorrected

$$H_C = H \cdot \left(\frac{\rho_0}{\rho} \right)^{0.7}$$

Homologous Representation of Data (Supercritical CO_2 at 7.6 Mpa, 305K)



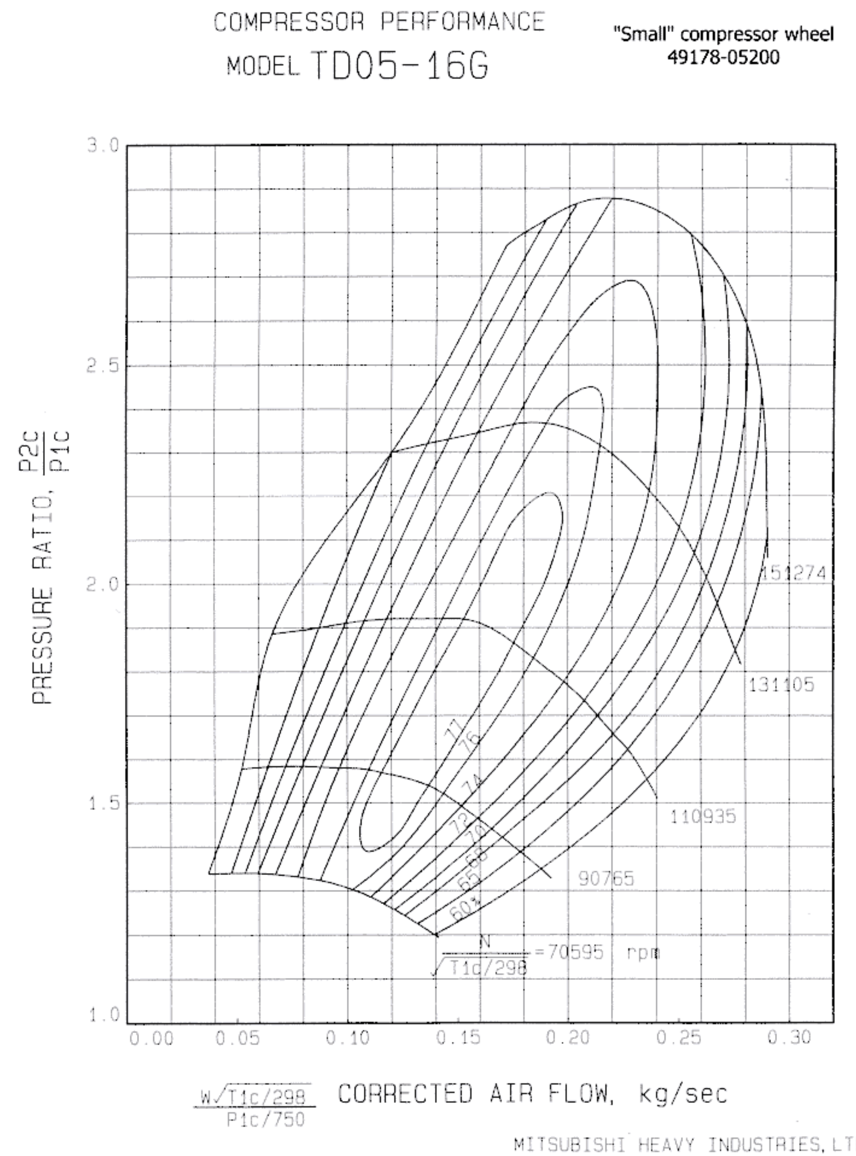
Head



Efficiency

Accuracy Comparison of Simple Linear Interpolation and Homologous Curves

- Estimate values for 110935 rpm speed curve.
- Simple linear interpolation between 90765-rpm and 131105-rpm curve at various flow rates
- Compare with density-corrected homologous representation
- Comparison made for Pressure Ratio and Efficiency



Results show that simple interpolation is better than homologous representation for head

$$\text{Fractional Error} = \frac{|\textbf{calculated} - \textbf{actual}|}{\textbf{actual}}$$

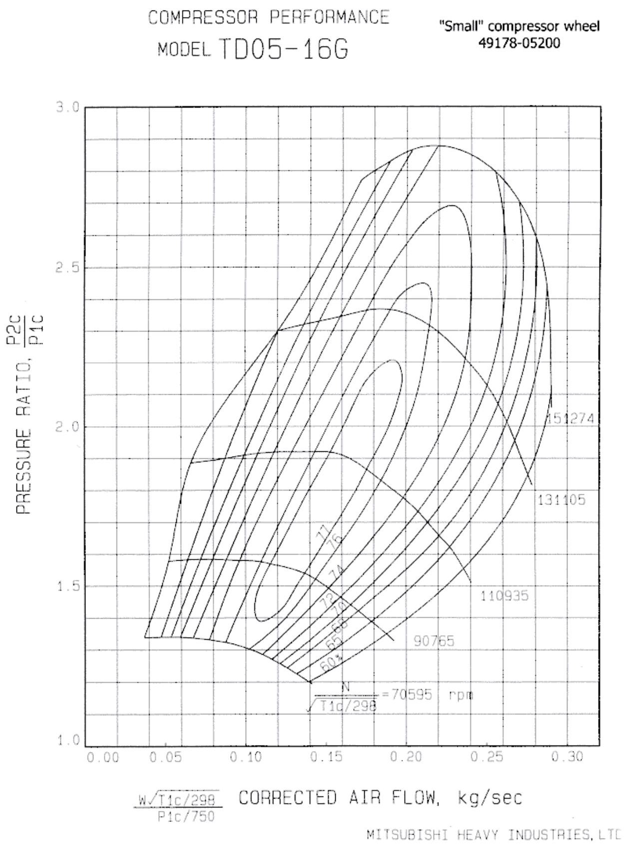
Flow Rate (kg/s)	Pressure Ratio	Interpolated	Fractional Error	Homologous	Fractional Error
0.12	1.920	1.933	0.007	1.923	0.002
0.14	1.923	1.918	0.003	1.907	0.008
0.16	1.910	1.903	0.004	1.846	0.034
0.18	1.849	1.872	0.012	1.796	0.029
mean			0.006		0.018
standard deviation			0.004		0.015

Results show that simple interpolation is worse than best-fit for efficiency

$$\text{Fractional Error} = \frac{|\textbf{calculated} - \textbf{actual}|}{\textbf{actual}}$$

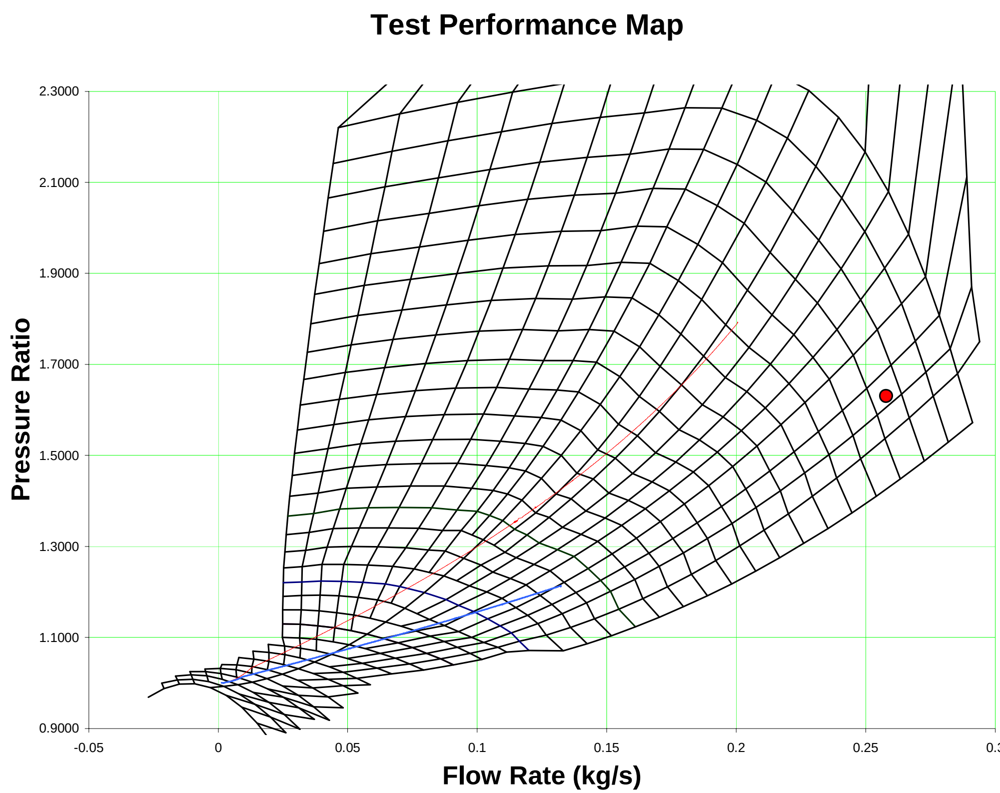
Flow Rate (kg/s)	η_{ad}	Interpolated	Fractional Error	Best-fit	Fractional Error
0.12	0.744	0.711	0.044	0.719	0.034
0.14	0.736	0.727	0.012	0.739	0.004
0.16	0.77	0.719	0.066	0.746	0.031
0.18	0.765	0.693	0.094	0.737	0.037
mean			0.054		0.026
standard deviation			0.035		0.015

Increased resolution and range of performance map based on automobile turbocharger compressor



A

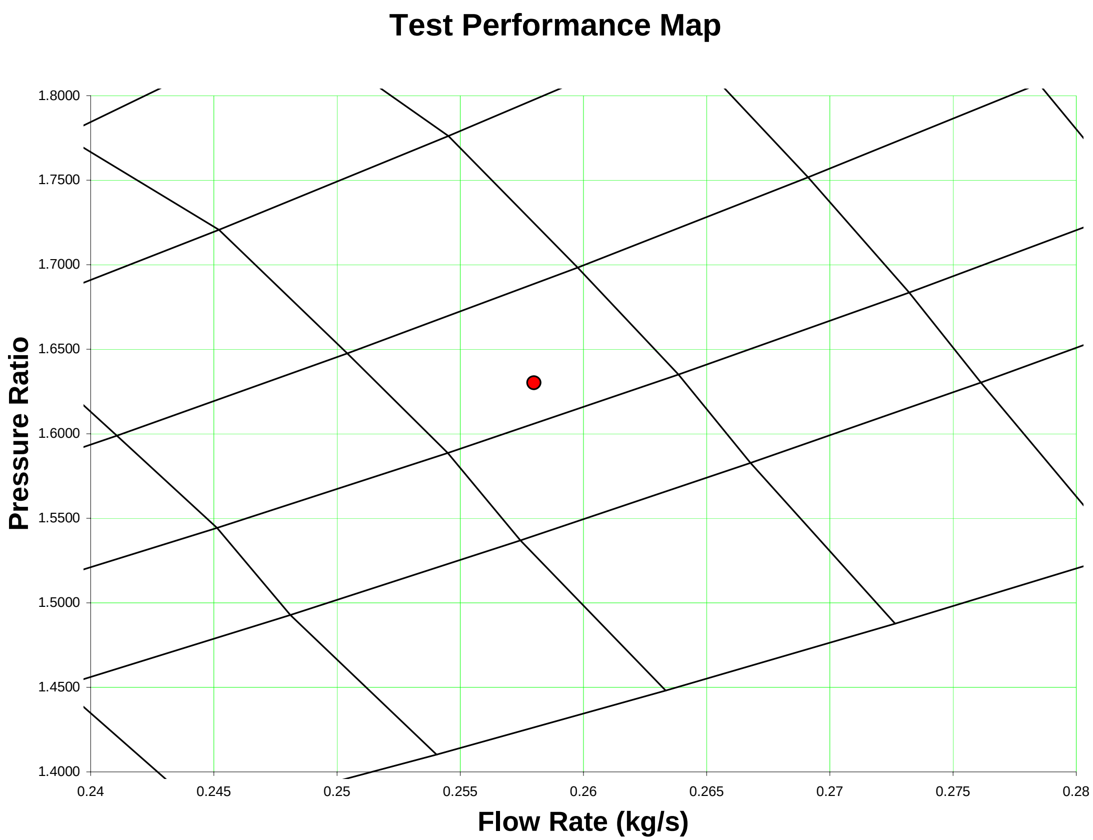
Performance Data



With Extrapolated and Interpolated Numbers

"Smart" interpolation based on efficiency

- *Bracket with Upper and Lower speed curve*
- *Choose Upper and Lower Flow Values based on efficiency*
  - *Decide whether closer to upper or lower speed curve*
    - *Shift data location of further-away point*
    - *Done when one end-point matches*
- *Special cases for edges of table*



Implementation of model in the code

Total pressure

$$P_2^T = P_2 + \frac{\alpha_f \rho_f \left| \bar{v}_f \cdot \dot{v}_f \right| + \alpha_g \rho_g \left| \bar{v}_g \cdot \dot{v}_g \right|}{2} \qquad (24)$$

Head

$$H = P_2^T \left(\frac{R_P - 1}{R_P} \right) \qquad (25)$$

Torque

$$\tau_T = \frac{-H \cdot \dot{m}}{\omega \cdot \eta \cdot \rho} \qquad (26)$$

where

$$\dot{m} = \dot{m}_J \quad and \quad \rho_{avg} = \frac{\rho_V + \rho_J}{2}$$

Dissipation

$$W_D = \tau_T \cdot \omega - H \cdot \left(\frac{\alpha_f \rho_f v_f + \alpha_f \rho_f v_f}{\alpha_f \rho_f + \alpha_f \rho_f} \right) \cdot A \qquad (27)$$

Results at Low Pressure Ratio

P_{in} = 90969 Pa, T_{in} = 300 K, R_P = 1.214, η = 0.647

	Theoretical Value	Code Value	Error
Compressor ΔP (Pa)	19452	19458	~0
Enthalpy Rise Δh (J/kg)	17159 (isentropic) 26601 (real)	27936	5%
Power (W)	3518	3695	

Torque (J)			
Isentropic	0.3252	0.3310	1.8%
Dissipative	0.1773	0.1805	
Total	0.5025	0.5115	

Density (kg/m^3)	1.1350	1.1151	1.8%

Power (W)			
Isentropic	2267	2307	1.8%
Dissipative	1236	1258	
Total	3503	3566	
Q_{Wall}		3694	

Results at High Pressure Ratio

P_{in} = 69371 Pa, T_{in} = 306 K, R_P = 1.793, η = 0.734

	Theoretical Value	Code Value	Error
Compressor ΔP (Pa)	55261	55372	0.2%
Enthalpy Rise Δh (J/kg)	55912 (isentropic) 76333 (real)	91227	20%
Power (W)	15309	18297	

Torque (J)

Isentropic	0.9618	1.0101	5%
Dissipative	0.3482	0.3657	
Total	1.3100	1.3758	

Density (kg/m^3)	0.9919	0.9445	5%

Work (Watts)

Isentropic	11174	11734	5%
Dissipative	4045	4248	
Total	15218	15982	
Q_{Wall}		18298	

High Pressure Ratio, No Dissipation

P_{in} = 69554 Pa, T_{in} = 303.7 K, R_P = 1.786, η = 1.0

	Theoretical Value	Code Value	Error
Enthalpy Rise Δh (J/kg)	55876	69052	24%
Internal Energy Rise Δu (J/kg)	49310	49450	0.3%
RELAP5-3D thermal energy eqn for steady, single-phase flow $(\dot{m}U)_j^{j+1} + \left(P\frac{\dot{m}}{\rho}\right)_j^{j+1} = \dot{Q}$ => $U_2 - U_1 + P_2\left[\frac{1}{\rho_2} - \frac{1}{\rho_1}\right] = \frac{\dot{Q}}{\dot{m}}$			
$P_2\left[\frac{1}{\rho_2} - \frac{1}{\rho_1}\right]$ (J/kg)		-49443	7 J/kg
Rewritten in terms of specific enthalpy, h $h_2 - h_1 - \frac{P_1 - P_2}{\rho_1} = \frac{\dot{Q}}{\dot{m}}$			
$\left[\frac{P_2 - P_1}{\rho_1}\right]$ (J/kg)	55876	69062	24%
$\left[\frac{P_2 - P_1}{0.5*(\rho_1 + \rho_2)}\right]$ (J/kg)	55876	56077	0.4%

High Pressure Ratio, Correction to Dissipation Term

P_{in} = 69480 Pa, T_{in} = 304.4 K, R_P = 1.789, η = 0.733

	Theoretical Value	Code Value	Error
Compressor ΔP (Pa)	55078	55203	0.2%
Enthalpy Rise Δh (J/kg)	76249	77938	2.2%

Power $[\dot{m} \cdot \Delta h]$ (W)	15229	15684	3%
Q_{Wall} (W)		15682	

Torque (J)

Isentropic	0.9578	0.9870	3%
Dissipative	0.3494	0.3601	
Total	1.3072	1.3471	

Density (kg/m^3)	0.9962	0.9666	3%

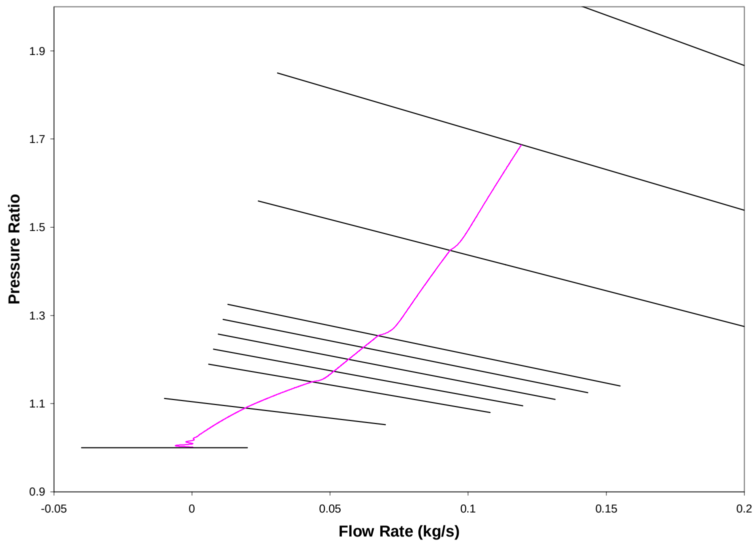
Power (W)

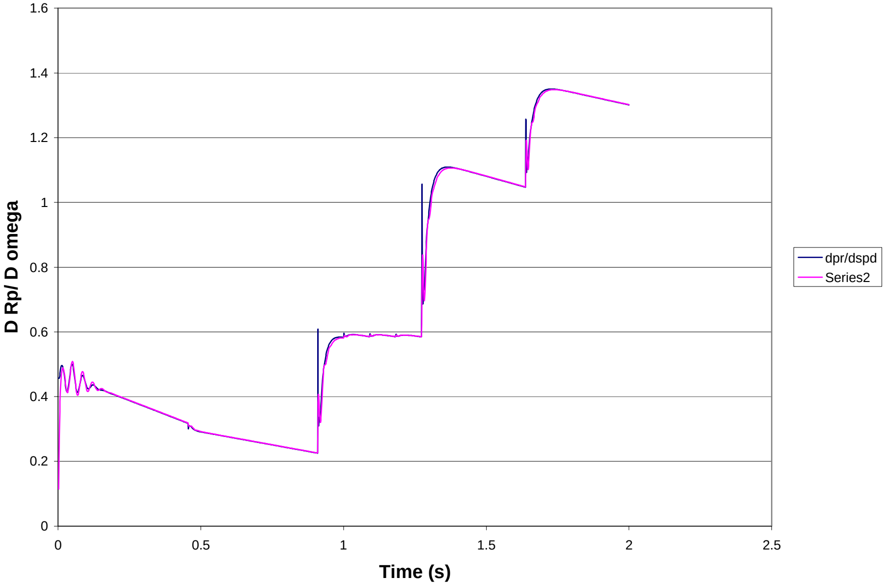
Isentropic	11127	11466	3%
Dissipative	4059	4183	
Total	15186	15649	

Internal Energy Rise Δu (J/kg)	55485	55820	0.6%

Linear interpolation is problematic

- *Investigate instability of model when crossing node lines*
- *Performance map simplified to end points*
- *Simplified model consists of flow boundary condition and compressor with speed table.*
- *Ramp calculation for 2 seconds*
  - *Zero to 0.01 kg/s*
  - *Zero to Rated Speed*
- *Discontinuity noted in $\Delta R_P / \Delta\omega$ at major nodes*
- *No discontinuity at minor nodes*
- *Time-averaged R_P (3 time steps) reduced severity*





Bicubic interplation

- *Method implemented but not yet functional*
  - *investigation in progress*
  - *funding suspended*
- *Requires finely identified data*
- *Feasibility questionable*
  - *may require orthogonal data*

Remaining Items and Issues

- Energy conservation (Resolved)
- Xmgr and Pygi
- Finalize method for data input
  - Performance map
    - Bicubic interpolator
    - Modified linear interpolation
  - Homologous
- Resolve performance data
  - Surge
  - Choking
  - Reverse flow and/or rotation
- Nearly-implicit

Conclusions

- *Compressor implementation similar to pump*
- *Performance characteristics need further analysis*
- *Additional work required to finalize model*
- *Need performance data*
- *Need transient information*