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New MELCOR Models Homologous Pumps

PRESENTED BY

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Homologous Pump Model Overview

- More mechanistic centrifugal pump model than previously available

- Model integrated into FL package, predicts the pump momentum source as a function of impeller speed, capacity (volumetric flow)

- Model computes:
  - Pressure head (hydraulic power = head x flow)
  - Hydraulic torque (brake power = hydraulic torque x speed)
  - Pump dissipation energy and pump efficiency
  - Pump speed via torque-inertia equation (also user-defined, optional trips)
  - Two-phase degradation effects

- For pump performance modeling, predict head and torque given speed and flow using built-in or user-defined data in a specialized “homologous” form

Homologous Pump Theory

- Pump performance model – homologous and polar homologous
  - Inputs: Impeller speed, ω, and pump volumetric flow (capacity), Q
  - Outputs: Pump head (H), hydraulic torque (T) exerted by fluid on impeller
  - Two-phase head/torque degradation via two-phase multiplier approach
  - Also a “universal correlation” option requiring less information from user

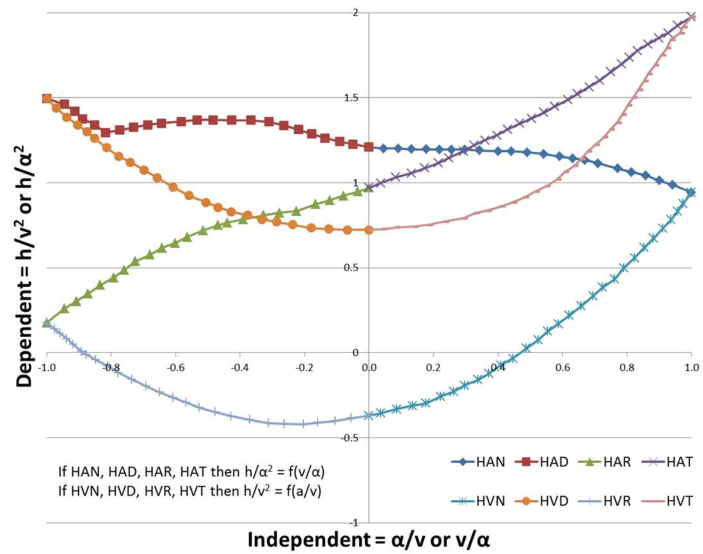
- Semi-implicit treatment of pump head in phasic velocity equations

- Pump speed control and the torque-inertia equation (TIE)
  - User controls and/or TIE can govern speed at different problem times
  - Pump trips available to arbitrarily model start-up, steady run, coast-down

- Other features
  - Friction torque generally modeled as a polynomial in ω/ω_R
  - Pump inertia generally modeled as a polynomial in ω/ω_R
  - Pump energy dissipation and efficiency

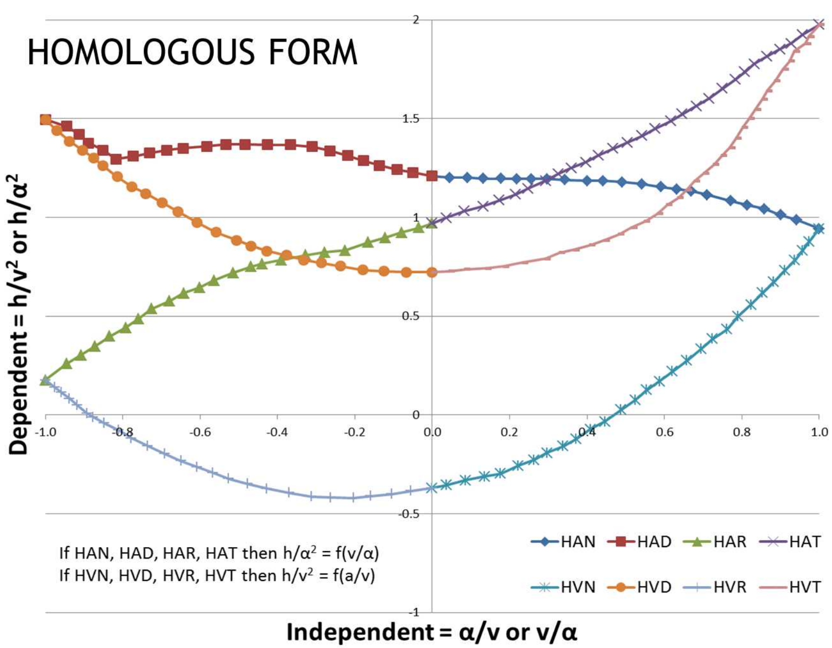
Homologous Pump Theory Pump Performance Model

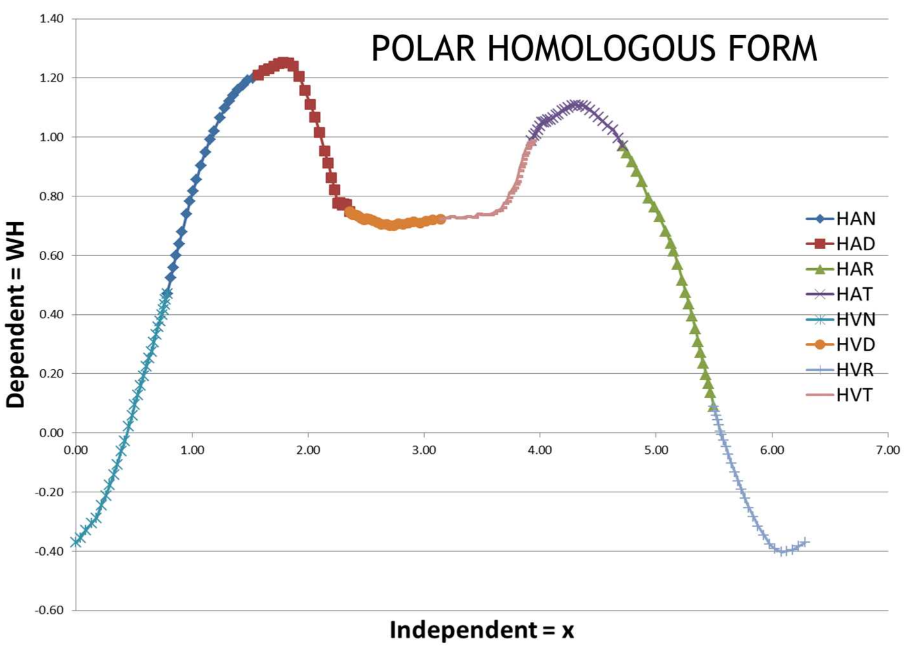
- Non-dimensional speed ($v = {}^{\omega}/_{\omega_R}$), flow ($\alpha = {}^{Q}/_{Q_R}$) with "rated" conditions
- Non-dimensional head ($h = {}^{H}/_{H_R}$), torque ($\tau = {}^{T}/_{T_R}$) with "rated" conditions
- Construct a plot covering the entire domain of pump operation
  - Four quadrants (normal, turbine, dissipation, reversal modes)
  - Two pieces per quadrant for a total of eight octants
  - Indep. var's ${}^{v}/_{\alpha}$ or ${}^{\alpha}/_{v}$
    - If $|{}^{v}/_{\alpha}| <= 1$, then use ${}^{v}/_{\alpha}$
    - If $|{}^{v}/_{\alpha}| > 1$, then $|{}^{\alpha}/_{v}| < 1$ and use ${}^{\alpha}/_{v}$
    - Independent variable bounded on [-1,1]
  - Dep var's for single/two-phase head/torque
    - If x is ${}^{v}/_{\alpha}$, dependent variable is ${}^{h}/_{\alpha^2}$ or ${}^{\tau}/_{\alpha^2}$
    - If x is ${}^{\alpha}/_{v}$, dependent variable is ${}^{h}/_{v^2}$ or ${}^{\tau}/_{v^2}$



Homologous Pump Theory Pump Performance Model

User gives homologous data, code converts to "polar homologous"





Practical difficulties with interpolation

- Which ind/dep variable forms apply
- Independent variable crosses zero

- Positive definite indep. var domain $[0,2\pi]$
- Single, non-overlapping curve
- Simply convert ind/dep variable space

Homologous Pump Theory Pump Performance Model

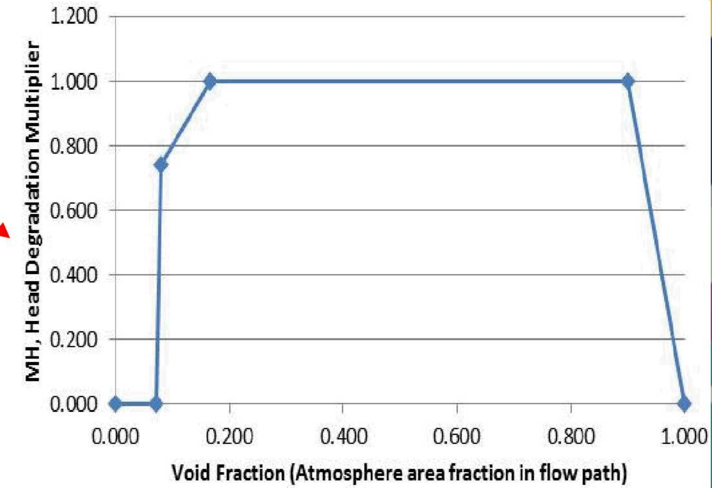
- Two-phase effects from two-phase head/torque curves and multipliers
- “Fully-degraded” curves for worst performance in two-phase conditions
- Use void-fraction-dependent “degradation multipliers”
- Overall equals single phase head/torque less a two-phase term

$$WH_{overall} = WH - MH * (WH - WH2)$$

$$WT_{overall} = WT - MT * (WT - WT2)$$

Subtract part of the difference between single/two phase

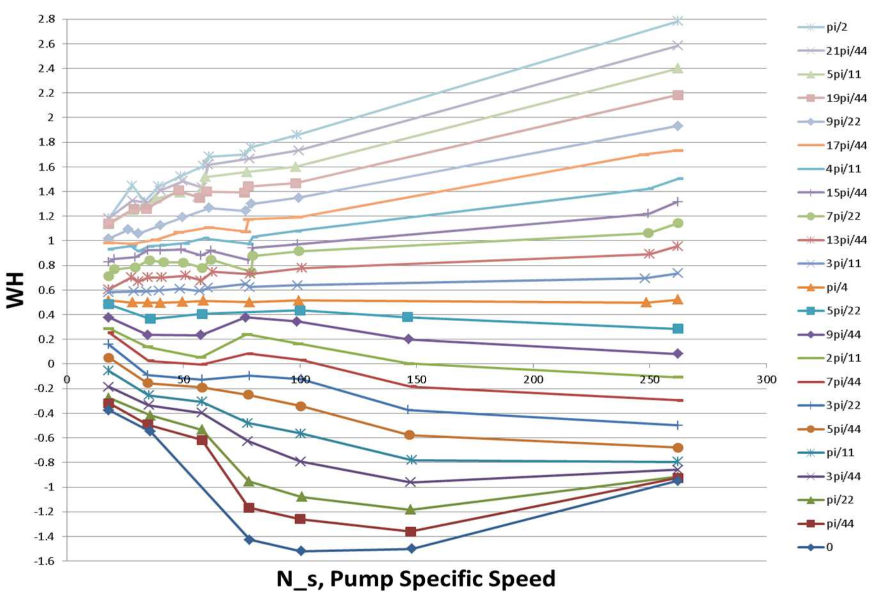
e.g. Semiscale MH



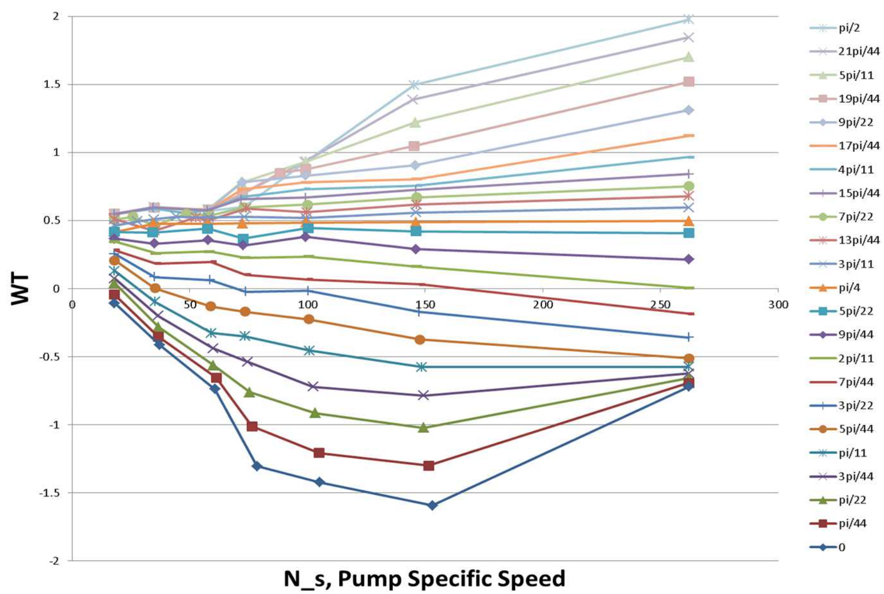
Homologous Pump Theory Pump Performance Model

- Universal correlation uses ω and Q to find H and T via data interpolation
- Use a data set compiled from several pump experiments
  - User gives pump specific speed, defined from rated quantities as: $N_s = \frac{\omega_R \sqrt{Q_R}}{{H_R}^{3/4}}$
  - Use N_s, ω, and Q to interpolate H and T functions
  - Valid for "normal", single-phase operation

X=f(ω,Q)



X=f(ω,Q)



Homologous Pump Theory, Semi-Implicit Head Treatment

Phasic Velocity Equation, FP j

$$\left(1+\frac{K^*_{j,\varphi}\Delta t}{2L_j}\left|v^{n-}_{j,\varphi}+v'_{j,\varphi}\right|+\frac{\alpha_{j,-\varphi}f_{2,j}L_{2,j}\Delta t}{\rho_{j,\varphi}L_j}\right)v^n_{j,\varphi} - \frac{\alpha_{j,-\varphi}f_{2,j}L_{2,j}\Delta t}{\rho_{j,\varphi}L_j}v^n_{j,-\varphi} + \sum_{s,\psi}C(j,\varphi:s,\psi)v^n_{s,\psi}$$

$$= v^{o+}_{j,\varphi} + \frac{K^*_{j,\varphi}\Delta t}{2L_j}\left|v'_{j,\varphi}\right|v^{n-}_{j,\varphi} + \frac{\Delta t}{\rho_{j,\varphi}L_j}\left(\hat{P}_i + \boxed{\Delta P_j} - \hat{P}_k\right) + (\rho\, g\Delta z)^o_{j,\varphi} + \frac{\partial(\rho\, g\Delta z)_{j,\varphi}}{\partial M_{i,P}}\left(\hat{M}^o_{i,P} - M^{o+}_{i,P}\right) + \frac{\partial(\rho\, g\Delta z)_{j,\varphi}}{\partial M_{k,P}}\left(\hat{M}^o_{k,P} - M^{o+}_{k,P}\right)\Bigg]$$

Explicit pressure head term, expand for semi-implicit treatment (new-time velocity factors into new-time head):

$$\Delta P_j = \Delta P_j^{n-1} + \left(\frac{d\Delta P}{dQ}\right)^{n-1}\left(Q_j^n - Q_j^{n-}\right)$$

$$\left(\frac{d\Delta P}{dQ}\right)^{n-1} = \rho_m g\left(\frac{dH}{dQ}\right)^{n-1} \qquad Q_j = Af\left(V_{j,P} + V_{j,A}\right)$$

$$\Delta P_j^{n-1} = \rho_m g H_j^{n-1} \qquad H_j^n = H_j^{n-1} + \left(\frac{dH}{dQ}\right)^{n-1}\left(Q_j^n - Q_j^{n-}\right)$$

Final expanded term:

$$\Delta P_j = \rho_m g H_j^{n-1} - \rho_m g A f\left(\frac{dH}{dQ}\right)^{n-1}\left(V^{n-}_{j,P}\right) - \rho_m g A f\left(\frac{dH}{dQ}\right)^{n-1}\left(V^{n-}_{j,A}\right) + \rho_m g A f\left(\frac{dH}{dQ}\right)^{n-1}\left(V^{n}_{j,\varphi}\right) + \rho_m g A f\left(\frac{dH}{dQ}\right)^{n-1}\left(V^{n}_{j,-\varphi}\right)$$

New phasic velocity equation:

$$V^n_{j,\varphi}\left(1+\left(\frac{K^*_{j,\varphi}\Delta t}{2L_j}\right)\left|V^{n-}_{j,\varphi}+V'_{j,\varphi}\right| + \left(\frac{\alpha_{j,-\varphi}f_{2,j}L_{2,j}\Delta t}{\rho_{j,\varphi}L_j}\right) - \zeta\left(\frac{\Delta t}{\rho_{j,\varphi}L_j}\right)\rho_m g A f\left(\frac{dH}{dQ}\right)^{n-1}\right) - V^n_{j,-\varphi}\left(\frac{\alpha_{j,-\varphi}f_{2,j}L_{2,j}\Delta t}{\rho_{j,\varphi}L_j} + \zeta\left(\frac{\Delta t}{\rho_{j,\varphi}L_j}\right)\rho_m g A f\left(\frac{dH}{dQ}\right)^{n-1}\right)$$

$$+\sum_{s,\Psi}\left[C(j,\varphi:s,\Psi)V^n_{s,\Psi}\right] = V^{o+}_{j,\varphi} + \left(\frac{K^*_{j,\varphi}\Delta t}{2L_j}\right)\left(\left|V'_{j,\varphi}\right|V^{n-}_{j,\varphi}\right) + \left(\frac{\Delta t}{\rho_{j,\varphi}L_j}\right)\left(\hat{P}_i + \left(\rho_m g H_j^{n-} - \zeta\rho_m g A f\left(\frac{dH}{dQ}\right)^{n-1}\left(V^{n-}_{j,\varphi}+V^{n-}_{j,-\varphi}\right)\right) - \hat{P}_k\right)$$

$$+(\rho g\Delta z)^o_{j,\varphi} + \frac{\partial(\rho g\Delta z)_{j,\varphi}}{\partial M_{i,P}}\left(\widehat{M}^o_{i,P} - M^{o+}_{i,P}\right) + \frac{\partial(\rho g\Delta z)_{j,\varphi}}{\partial M_{k,P}}\left(\widehat{M}^o_{k,P} - M^{o+}_{k,P}\right)$$

If ζ = 1 use semi-implicit formulation
if ζ=0 revert to fully explicit formulation

Homologous Pump Theory Semi-Implicit Head Treatment

- Derivative dH/dQ must be evaluated at time level n-1 (i.e. at $Q|_{n-1}$ or equivalently at polar homologous variable $x(\omega|_{n-1}, Q|_{n-1})$)

- Recently switched from a Lagrange polynomial approach

- Use a cubic spline fit to polar homologous head such that, for any given polar homologous independent variable $x(\omega,Q)$, can interpolate dH/dQ

- Calculated once to evaluate the fitting and uses spline fit parameters during the transient

Homologous Pump Theory Speed Control

- Three options:
  1. Pump speed always under CF/TF control
  2. Pump speed always governed by TIE
  3. Pump speed under CF/TF control until a pump trip transfers control to TIE

- TIE: $I_p \frac{d\omega}{dt} = \tau_{net} = \tau_{motor} - (\tau_H + \tau_{fr})$
  - User-supplied motor and friction torque, hydraulic torque from model
  - Net positive torque causes speed increase and vice-versa
  - Pump-to-motor connection subject to trip
    - If no trip applies (option 2 above), motor torque always under user control
    - If trip applies (option 3 above), then:
      - OFF state of trip – pump speed under CF/TF control
      - ON-FORWARD state of trip – pump disconnected from motor, thus τ_{motor} is zero
      - ON-REVERSE state of trip – pump connected to motor, τ_{motor} given by CF/TF

- Solve by FE: $\omega^n = \omega^{n-1} + \frac{\tau_{net}(\omega^{n-1})}{I_p(\omega^{n-1})}\Delta t$ OR BE/FPE: $\omega^n{}_{[0]} = \omega^{n-1}$

$$\omega^n{}_{[i+1]} = \omega^{n-1} + \frac{\tau_{net}(\omega^n{}_{[i]})}{I_p(\omega^n{}_{[i]})}\Delta t$$

FE= Forward Explicit
BE=Backwards Explicit

Homologous Pump Theory Other Features

- Pump friction torque (factors into TIE), generally a polynomial function:

$$\tau_{fr} = \begin{cases} \pm\,\tau_{frn}\,, for \left|\frac{\omega}{\omega_R}\right| < S_{PF} \\ \pm\left(\tau_{fr0} + \tau_{fr1}\left|\frac{\omega}{\omega_R}\right|^{x1} + \tau_{fr2}\left|\frac{\omega}{\omega_R}\right|^{x2} + \tau_{fr3}\left|\frac{\omega}{\omega_R}\right|^{x3}\right), for \left|\frac{\omega}{\omega_R}\right| \geq S_{PF} \end{cases}$$

- Pump inertia (factors into TIE), generally a polynomial function:

$$I_p = \begin{cases} I_{pn}\,, for \left|\frac{\omega}{\omega_R}\right| < S_{PI} \\ \left(I_{P0} + I_{P1}\left|\frac{\omega}{\omega_R}\right| + I_{P2}\left|\frac{\omega}{\omega_R}\right|^{2} + I_{P3}\left|\frac{\omega}{\omega_R}\right|^{3}\right), for \left|\frac{\omega}{\omega_R}\right| \geq S_{PI} \end{cases}$$

- Pump energy dissipation and efficiency
  - Total power delivered by impeller to fluid (“brake power”) : $\tau_H * \omega * {}^{2\pi}/_{60}$
  - Not all brake power translates into “hydraulic power”: $gH\left((1-\alpha_g)\rho_f V_f + \alpha_g \rho_g V_g\right)Af$
  - The difference is “dissipation” due to inefficiency:

$$DISS = \tau_H \omega \frac{2\pi}{60} - gH\left((1-\alpha_g)\rho_f V_f + \alpha_g \rho_g V_g\right)Af \qquad EFF = \frac{gH\left((1-\alpha_g)\rho_f V_f + \alpha_g \rho_g V_g\right)Af}{\tau_H * \omega * \frac{2\pi}{60}}$$

  - Add dissipation as thermal energy to pump discharge CV

Homologous Pump Theory Other Features

- Model is implemented through FP, expand existing **FL_PMP**
- **FL_PMP**, field 4, now has two new possibilities for **PTYPE**
  - **HOM** – User specifies a complement of homologous pump data or use built-in
    - New fields 5 and 6 if field 4 sets **PTYPE** to **HOM**
    - Field 5 is **PHSOPT**, set to **ONE** for single-phase, set to **TWO** for two-phase
    - Field 6 is **DATOPT**, set to **USER** for user data, set to **SEMI** or **LOFT** for built-in
  - **UNIV** – User gives specific speed, opts for interpolation of **UNIV** model data
    - New fields 5 and 6 if field 4 sets **PTYPE** to **UNIV**
    - Field 5 is **PHSOPT**, same as above but note if a departure from single phase occurs, the model defaults to **PTYPE** = **HOM** and **DATOPT** = **SEMI**
    - Field 6 is **DATOPT**, pertains to single phase dissipation, normal, and reversal

```
FL_PMP 3 ! N   PNAME      FLNAME    PTYPE   PHSOPT  DATOPT  ITRIP  CF/TFNAME
           1 ‘PUMP_1’   ‘FL101’   HOM     ONE     USER    ON                 ! ITRIP is ON, pump not subject to trip
           2 ‘PUMP_2’   ‘FL102’   HOM     TWO     SEMI    CF     ‘CF101’     ! Use a built-in Semiscale data, CF trip
           3 ‘PUMP_3’   ‘FL103’   UNIV    ONE     SEMI    TF     ‘TF101’     ! Use UNIV model, TF trip
```

Homologous Pump User Input

- New records for rated pump conditions, pump performance model data:
  - **FL_RPD** – Specify rated pump data, required if **PTYPE** is **HOM** or **UNIV**
    - Pump object number and object name
    - Complement of rated conditions: **OMEGAR, SPDRAT, QR, HR, PSHR, RHOR**
    - Rated speed, initial-to-rated speed, rated capacity, head, shaft power, density

```
FL_RPD 1 ! N   PNAME    OMEGAR  SPDRAT    QR      HR      PSHR      RHOR
           1 'PUMP1' 3560.0   0.0    0.0114 58.52 1.769E+4 997.95     ! PSHR = (rated hyd torque)*OMEGAR
```

  - **FL_SPH** – Single phase head performance data, required if **PTYPE** is **HOM** and **DATOPT** is **USER**
    - Name TF's for pump data, the two N mode octants are required (other 6 optional)
    - Fields for each octant: **HAN, HVN, HAD, HVD, HAT, HVT, HAR, HVR**
    - Use placeholders '-' for excluded octants
    - Also have analogous **FL_SPT**, **FL_TPH**, and **FL_TPT** for single phase torque and two phase head/torque

```
FL_SPH 2 ! N   PNAME     HAN      HVN      HAD      HVD      HAT      HVT      HAR      HVR
           1 'PUMP1'  'HANTF'  'HVNTF'  'HADTF'  'HVDTF'  'HATTF'  'HVTTF'  'HARTF'  'HVRTF'
           2 'PUMP2'  'HANTF'  'HVNTF'  'HADTF'  'HVDTF'    '-'      '-'      '-'      '-'
```

Homologous Pump User Input

- New records for friction torque and inertia, numerical treatment:
  - **FL_PFR** – Specify coefficients, exponents of pump friction torque polynomial
    - Four coefficients, three exponents, one critical speed ratio
    - Recall a constant friction torque is used if below a critical speed ratio

```
FL_PFR 1 ! N  PNAME     TCOEFFC  TCOEFF1  TCOEFF2  TCOEFF3  TEXP1  TEXP2  TEXP3  TFRC   TSPCRT
           1 'PUMP1'   451.0    100.0    50.0     25.0     1.1    2.2    3.3    451.0  0.25
```

  - **FL_PIN** – Specify coefficients of the pump inertia polynomial
    - Four coefficients, one critical speed ratio
    - Recall a constant inertia is used if below a critical speed ratio

```
FL_PIN 1 ! N  PNAME     ICOEFFC  ICOEFF1  ICOEFF2  ICOEFF3  INRC   ISPCRT
           1 'PUMP1'   1.43     1.0      0.5      0.25     1.43   0.25
```

  - **FL_PNT** – Pump numerical treatment (in velocity eqns, for diss. energy)
    - First field is **PNTOPT**, either **SIMP** or **EXP** for semi-implicit or explicit head
    - Second field is **DISOPT**, either **YES** or **NO** to dissipation energy source term

```
FL_PNT 1 ! N  PNAME     PNTOPT  DISOPT
           1 'PUMP1'   SIMP    YES
```

Homologous Pump User Input

- New record for pump speed control and motor torque specification
  - **FL_SMT** – Specify speed control mechanism, motor torque, and CFs/TFs
    - Speed control, third through fifth fields
      - 3rd : **SMTOPT** – **CFTF-ONLY|CFTF-TIE|TIE**
      - 4th : **SFLAG** – **NO|CF|TF** (NO CF/TF control, CF control, or TF control)
      - 5th : '-', 'CFNAME', 'TFNAME'
    - Motor torque, fifth through seventh fields
      - 6th : **MTFLAG** – **NO|CF|TF** (NO CF/TF control, CF control, or TF control)
      - 7th : '-', 'CFNAME', 'TFNAME'
    - If no motor torque CF/TF, the constant value is implied by rated conditions

```
FL_SMT 1 !  N  PNAME        SMTOPT     SFLAG    CF/TFNAME     MTFLAG    CF/TFNAME
            1 'PUMP1'   CFTF-ONLY   CF   'OMEGA_CF'    CF     'TAUMOT_CF'
            2 'PUMP2'   CFTF-TIE    TF   'OMEGA_TF'    NO        '-'
            3 'PUMP3'     TIE       NO       '-'       TF     'TAUMOT_TF'
```