Fan and Pump Efficiency in Modelica Based on the Euler Number

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Building Energy 1

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Background

- Fan power from flow work

$$\eta = \frac{\dot{W}_{flo}}{P} = \frac{\dot{V} \cdot \Delta p}{P}$$

$$P = \frac{\dot{W}_{flo}}{\eta} = \frac{\dot{V} \cdot \Delta p}{\eta}$$

  - ✖ $P(\dot{V} \to 0, \eta = const) \to 0$
  - ✔ $\eta(\dot{V} \to 0, P > 0) \to 0$

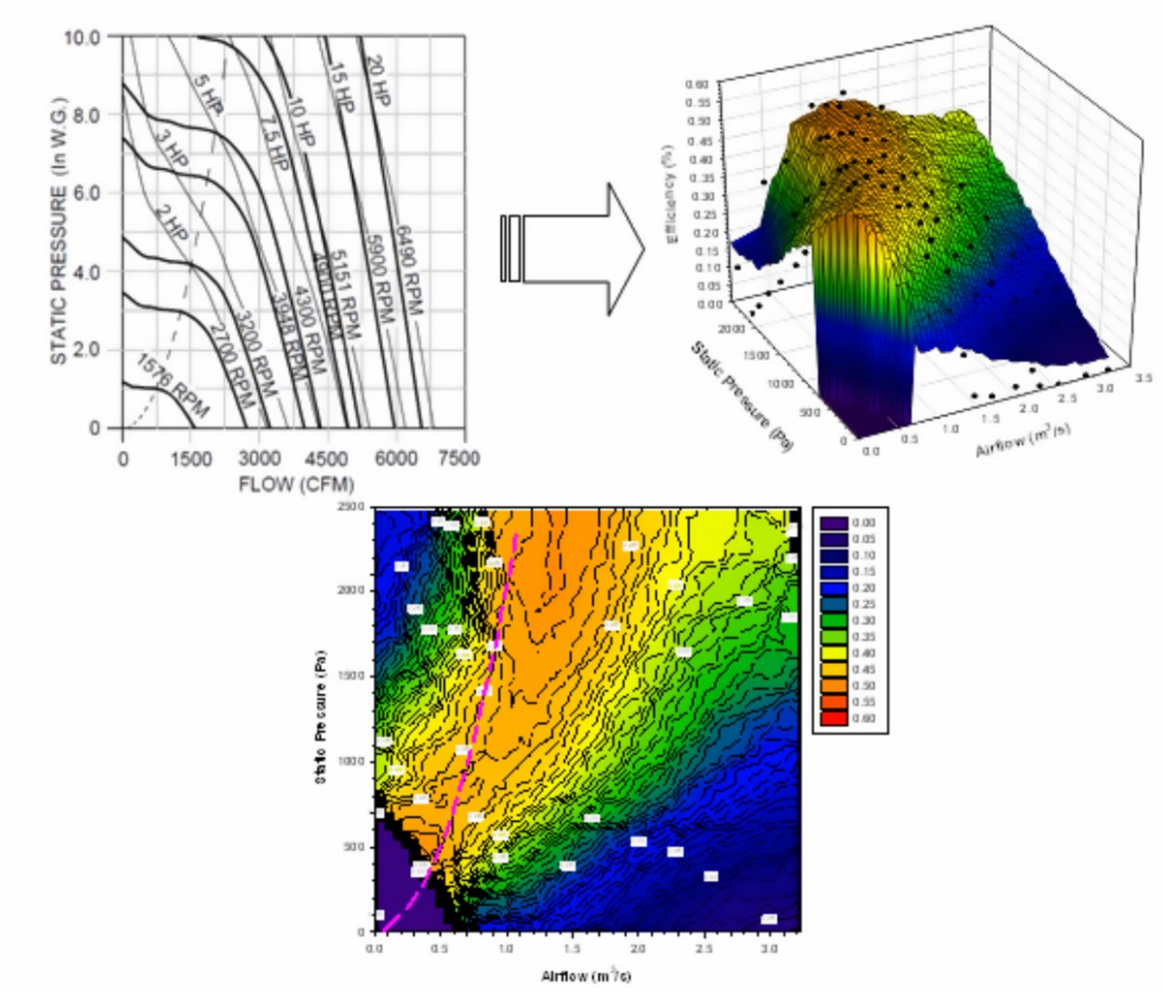


Figure 16.16: Example Fan Performance Maps - Manufacturer's Data from Loren Cook Company, plus Derived Static Efficiency (Three-Dimensional and Contours) (Dashed Parabolic Curve is "Do Not Select Line")

EnergyPlus v9.4 Engineering Reference. https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v9.4.0/EngineeringReference.pdf

Background

- Fan power from flow work

  $$\eta = \frac{\dot{V} \cdot \Delta p}{P}$$

  $$P = \frac{\dot{V} \cdot \Delta p}{\eta}$$

  - ✖ $P(\dot{V} \rightarrow 0, \eta = const) \rightarrow 0$
  - ✔ $\eta(\dot{V} \rightarrow 0, P > 0) \rightarrow 0$
- Matters especially when:
  - $\dot{V}$ is low, while
  - Δp is maintained at a certain level

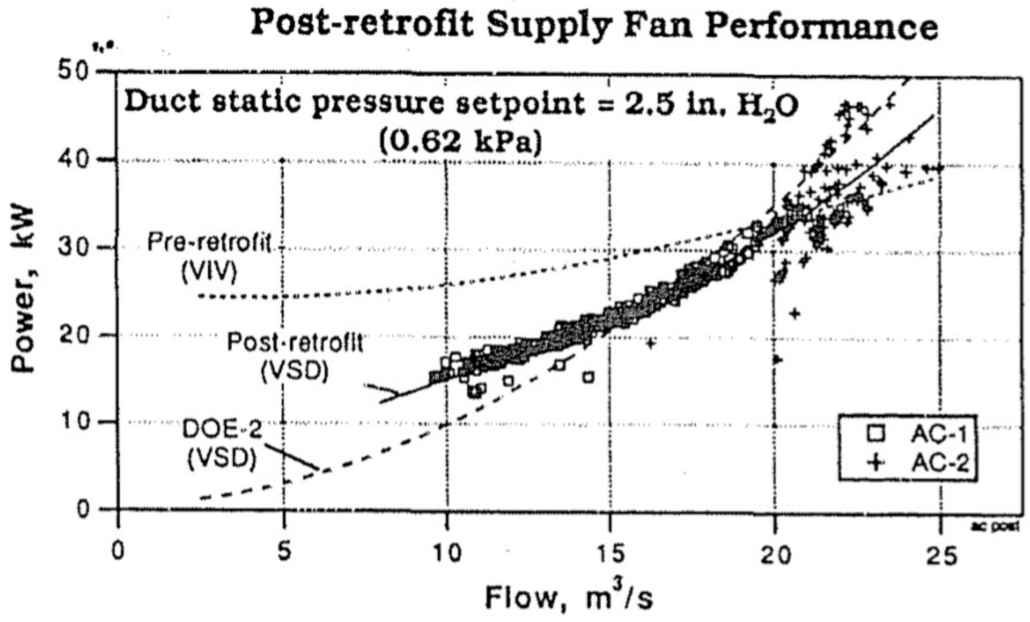
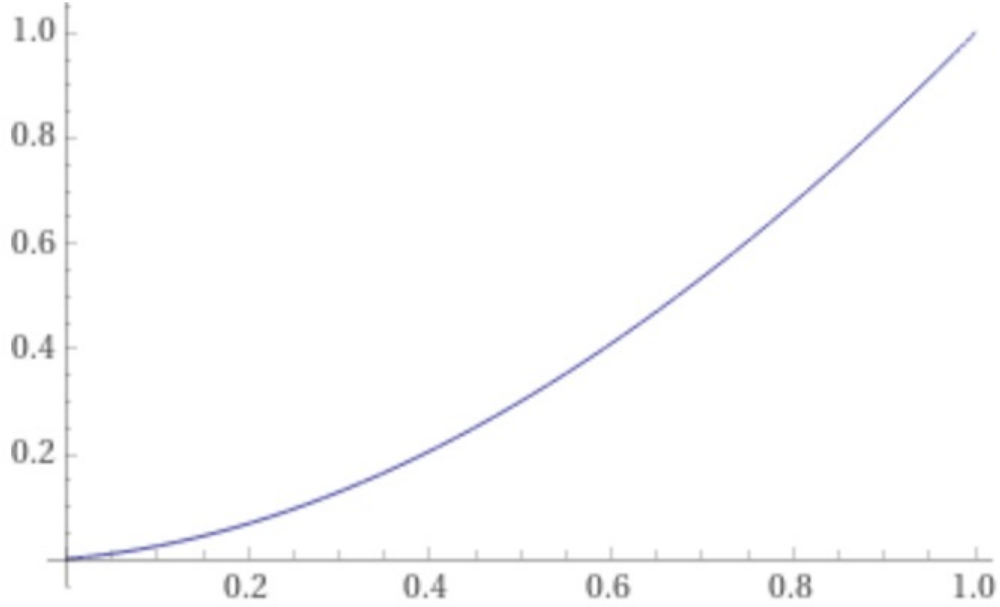


Figure 5
S.L. Englander and L.K. Norford (1992a). "Saving fan energy in VAV systems - part 1: Analysis of a variable speed drive retrofit." ASHRAE Transactions (98).

Background



- Typical simulation software often simplifies $P(\dot{V}, \Delta p)$ to $P(\dot{V})$ through the part load ratio (PLR).
  - ASHRAE Standard 90.1-2020 Table G3.1.3.15

$$P/P_d = 0.0013 + 0.1470PLR + 0.9506PLR^2 - 0.0998PLR^3$$

where P/P_d is the ratio between the power consumption and the design power consumption, and $PLR = \dot{V}/\dot{V}_d$ is the ratio between the flow rate and the design flow rate.

  - Default curve in many simulation programmes.
  - Makes implicit assumptions about the system curve.

Methodology
Euler Number

The Euler number (for any medium)

$$Eu = \frac{\text{pressure forces}}{\text{inertial forces}}$$

$$= \frac{\Delta p \ A}{p_d \ A} = \frac{\Delta p}{p_d} = \frac{2 \ \Delta p \ A^2}{\rho \ \dot{V}^2}$$

where $p_d = \frac{v^2 \ \rho}{2} = \frac{\dot{V}^2 \ \rho}{2 \ A^2}$ – dynamic pressure,

A – characteristic area

Methodology
Euler Number

The Euler number (for any medium)

$$Eu = \frac{2\ \Delta p\ A^2}{\rho\ \dot{V}^2}$$

Modified Euler number (U.S. DOE, 2021; Haves et al., 2014)

$$Eu^* = \frac{\Delta p\ D^4}{\rho\ \dot{V}^2}$$

EnergyPlus v9.4 Engineering Reference. https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v9.4.0/EngineeringReference.pdf

Haves, Philip et al. (2014-09). Development of Diagnostic and Measurement and Verification Tools for Commercial Buildings. Tech. rep. CEC-500-2015-001. Lawrence Berkeley National Laboratory.

Methodology
Euler Number

$$\frac{\eta}{\eta_p} = f\left(\frac{Eu}{Eu_p}\right)$$

- Sub p: peak, i.e. where $\eta = \eta_{max}$

$$Eu = \frac{\Delta p \cdot D^4}{\rho \cdot \dot{V}}$$

$$\frac{Eu}{Eu_p} = \frac{\Delta p}{\dot{V}^2} \cdot \frac{\dot{V}_p^2}{\Delta p_p}$$

User input needed:

$\eta_p, \Delta p_p, \dot{V}_p$

* η is hydraulic efficiency

* Eu is modified Euler number

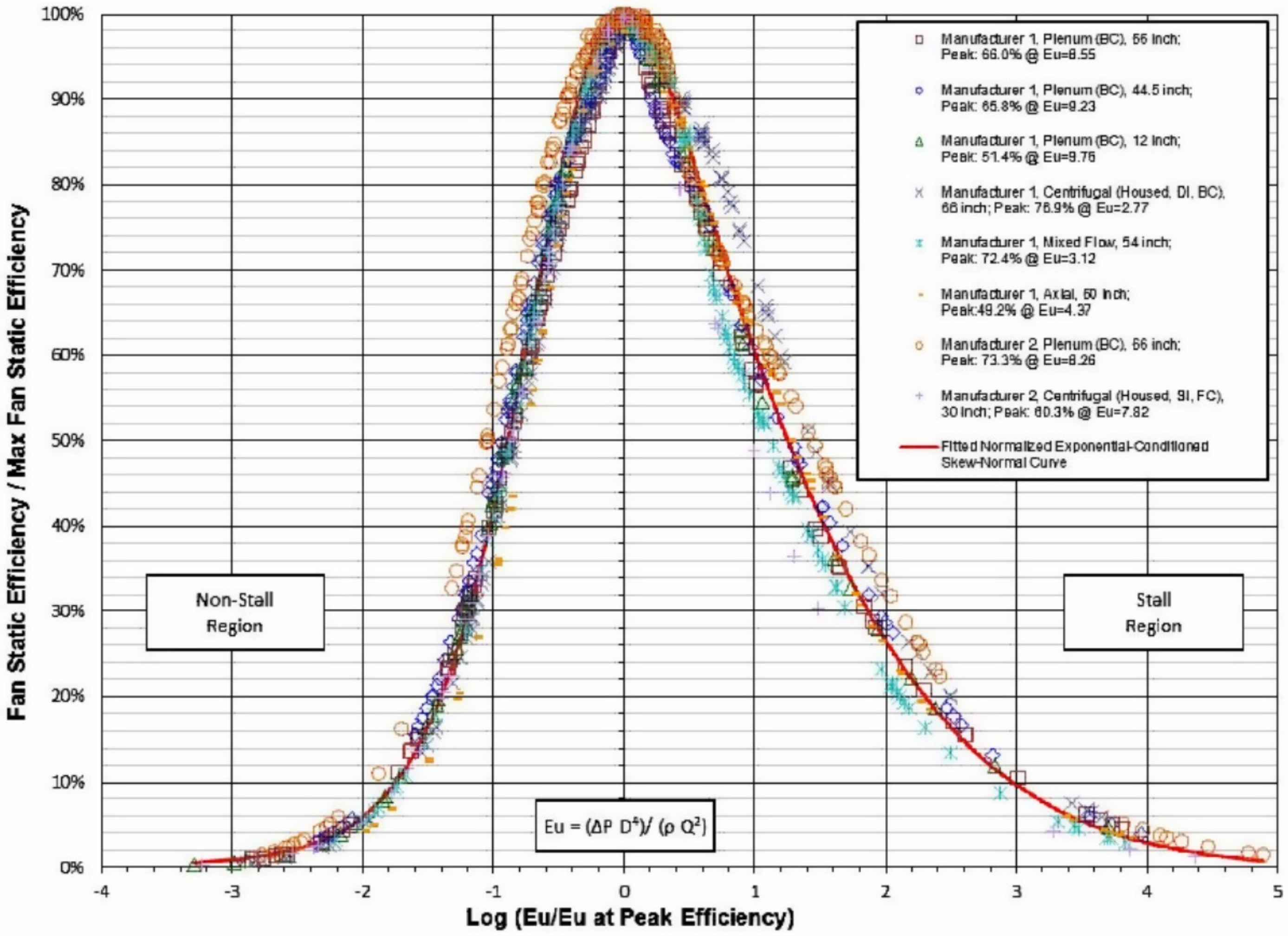


Figure 16.17: Normalized Efficiency Curves for Eight Fans in Dimensionless Space *(BC = backward curved, FC = forward curved; SI = single inlet, DI = double inlet)*

EnergyPlus v9.4 Engineering Reference. https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v9.4.0/EngineeringReference.pdf

Methodology Euler Number

$$\frac{\eta_{hyd}}{\eta_{hyd,p}} = \frac{\exp(-0.5Z_1^2)\left(1+\frac{Z_2}{|Z_2|}\operatorname{erf}\left(\frac{|Z_2|}{\sqrt{2}}\right)\right)}{\exp(-0.5Z_3^2)\left(1+\frac{Z_3}{|Z_3|}\operatorname{erf}\left(\frac{Z_3}{\sqrt{2}}\right)\right)},$$

where

$$Z_1 = (x-a)/b,$$
$$Z_2 = (\exp(cx)\,dx-a)/b,$$
$$Z_3 = -a/b,$$
$$x = \log_{10}(Eu^*/Eu_p^*),$$

and

$$a = -2.732094,$$
$$b = 2.273014,$$
$$c = 0.196344,$$
$$d = 5.267518.$$

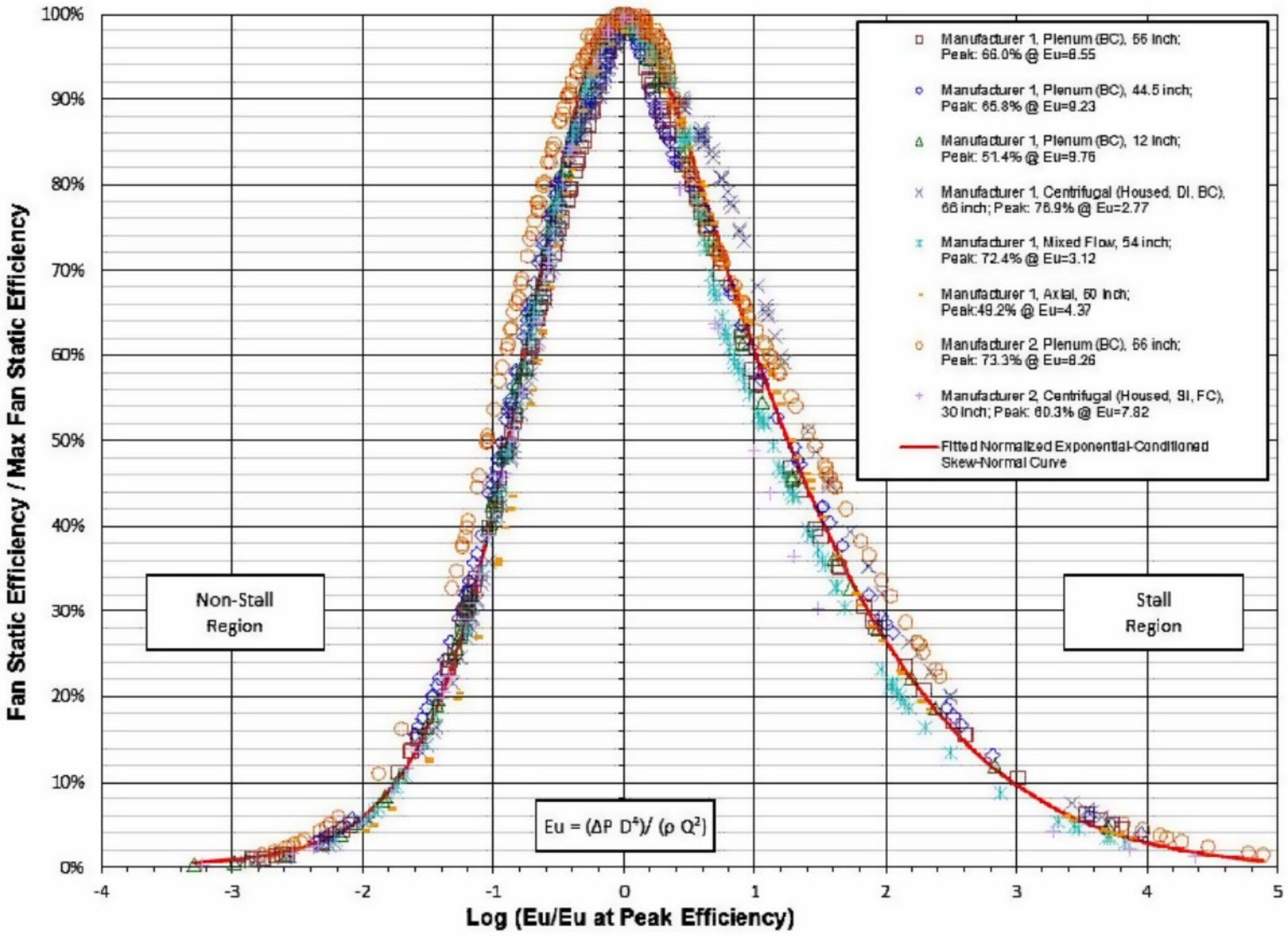


Figure 16.17: Normalized Efficiency Curves for Eight Fans in Dimensionless Space *(BC = backward curved, FC = forward curved; SI = single inlet, DI = double inlet)*

EnergyPlus v9.4 Engineering Reference.
https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v9.4.0/EngineeringReference.pdf

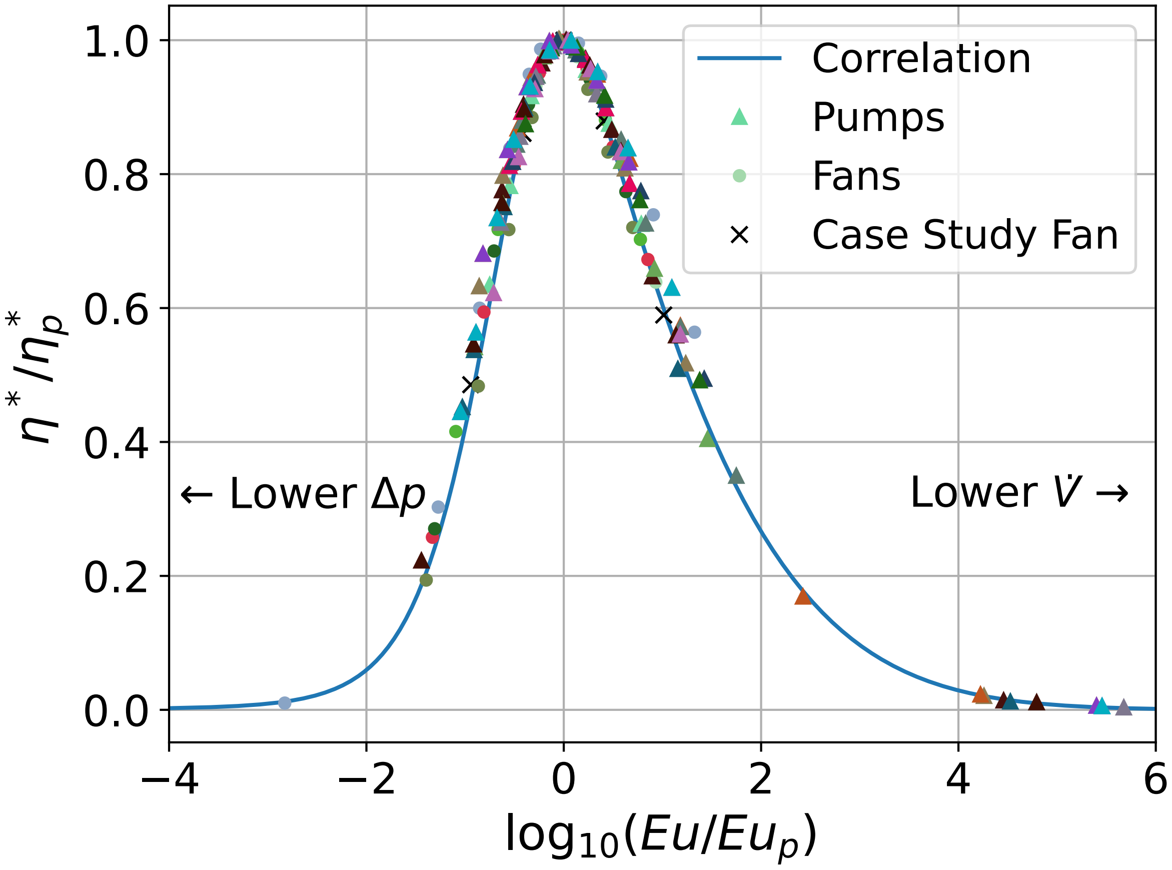
Methodology
Euler Number

Works on pump data as well.

$$Eu = \frac{2\ \Delta p\ A^2}{\rho\ \dot{V}^2}$$

$$Eu^* = \frac{\Delta p\ D^4}{\rho\ \dot{V}^2}$$

$$\frac{Eu}{Eu_p} = \frac{Eu^*}{Eu_p^*}$$



Modelica Implementation

Modelica Buildings Library

- A free open-source library with dynamic simulation models for building energy and control systems
- https://github.com/lbl-srg/modelica-buildings
- https://simulationresearch.lbl.gov/modelica/

(Model currently under development branch, issue #2668)

Michael Wetter, Wangda Zuo, Thierry S. Nouidui and Xiufeng Pang. Modelica Buildings library. *Journal of Building Performance Simulation*, 7(4):253-270, 2014.

Modelica Implementation Efficiency and power items

- Total efficiency $\eta = \frac{\dot{W}_{flo}}{P}$
- Hydraulic efficiency $\eta_{hyd} = \frac{\dot{W}_{flo}}{\dot{W}_{hyd}}$
  - *Hydraulic work* aka *shaft work* or *brake horsepower*
  - The one applicable to the correlation
- Motor efficiency $\eta_{mot} = \frac{\dot{W}_{hyd}}{P}$
  - Otherwise handled

$$P \xrightarrow{\eta_{mot}} \dot{W}_{hyd} \xrightarrow{\eta_{hyd}} \dot{W}_{flo}$$

$$P = \frac{\dot{V}\ \Delta p}{\eta_{hyd}\, \eta_{mot}}$$

Modelica Implementation
Efficiency and power items

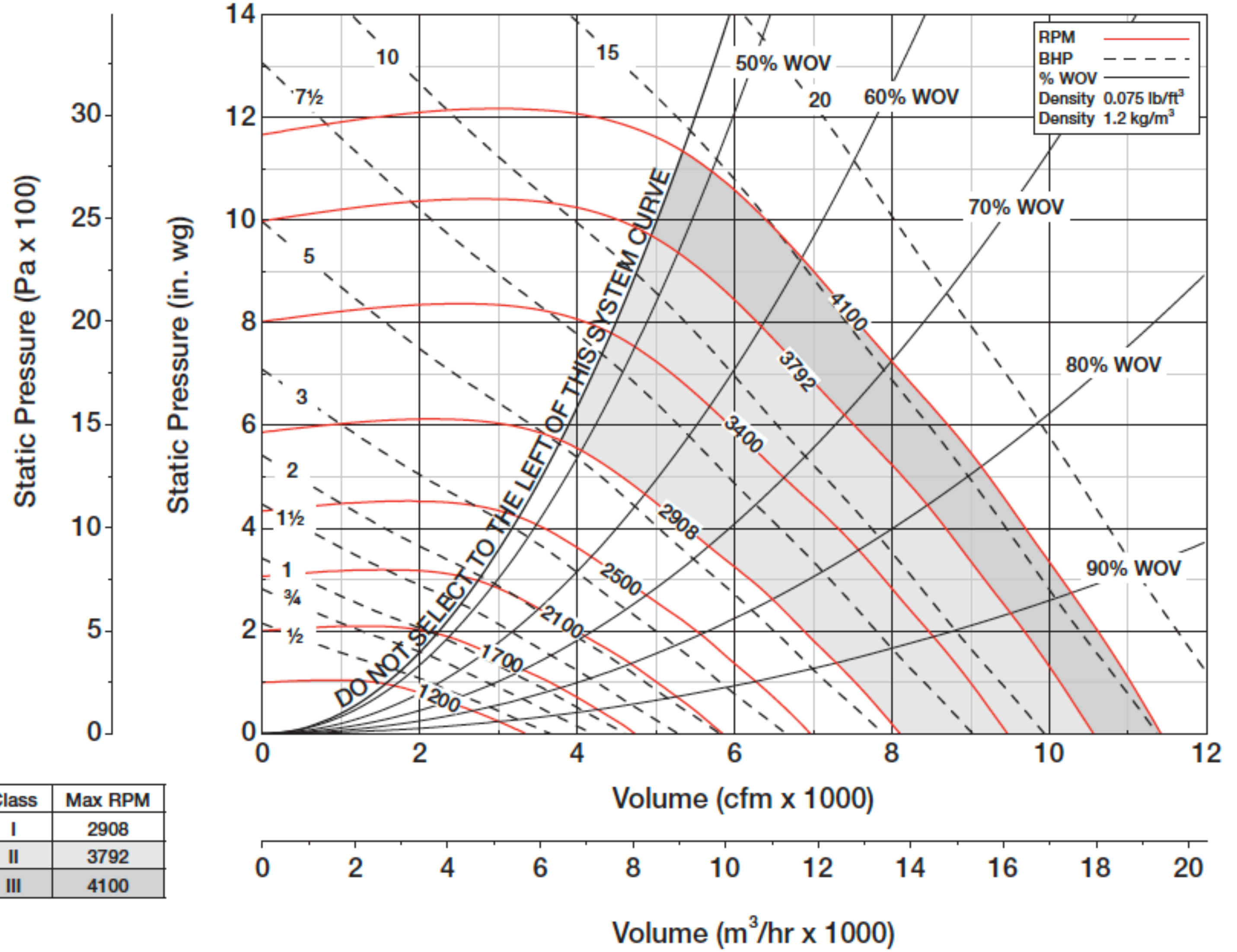
$\dot{W}_{hyd}(\dot{V}, \Delta p)$ and $\eta_{hyd}(\dot{V}, \Delta p)$ are implemented with `Modelica.Blocks.Tables.CombiTable2Ds`.

- Avoids evaluating the correlation function which is computationally expensive and not globally differentiable,
- Avoids $\log\left(\frac{0}{0}\right)$ more easily in $\log_{10}\left(\frac{Eu}{Eu_p}\right)$,
- Avoids $\frac{0}{0}$ more easily in $P = \frac{\dot{V} \cdot \Delta p}{\eta}$ as $(\dot{V}, \eta) \to (0,0)$.

Validation

- Nominal speed
  - Eighteen sets of pump data
  - Seven sets of fan data
- Reduced speed
  - One fan looked at in detail

13 BIDW



Class	Max RPM
I	2908
II	3792
III	4100

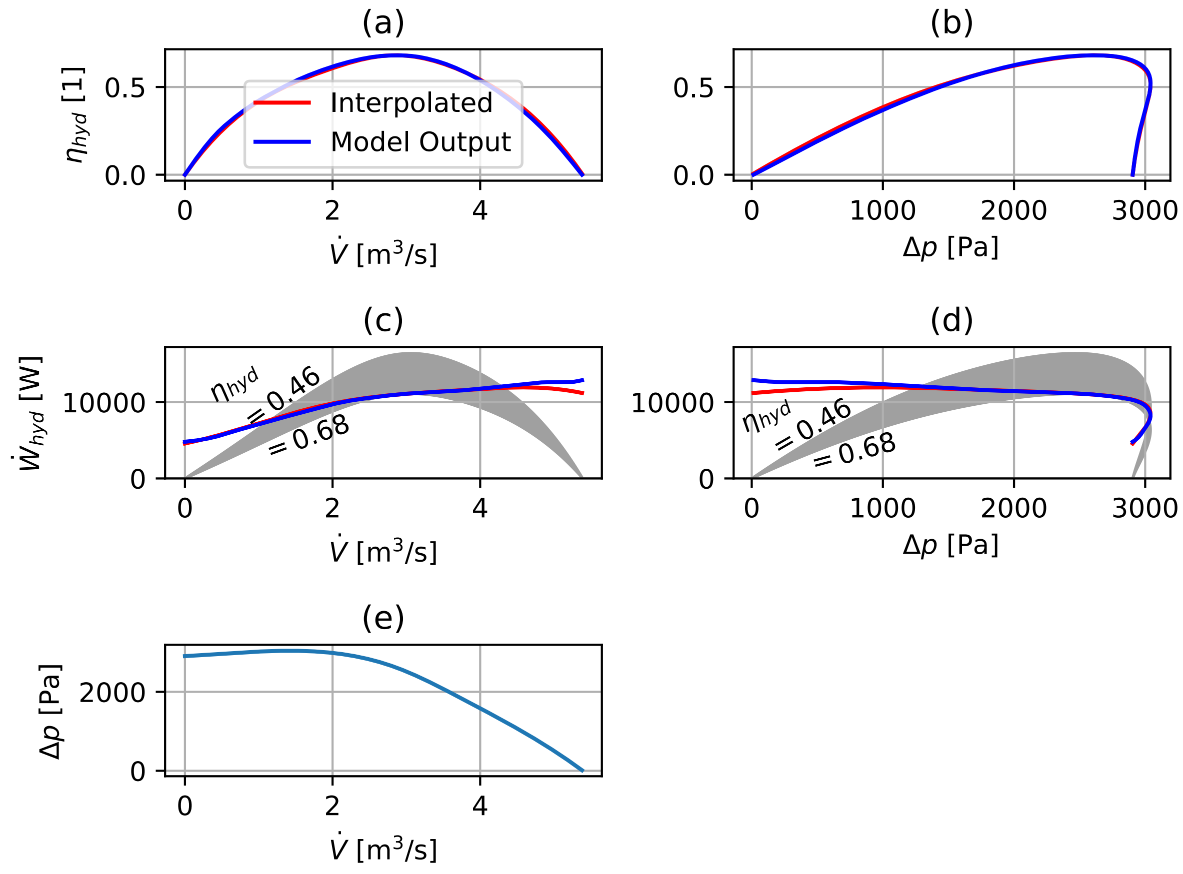
% WOV = (CFM X 100) / (RPM X 2.79)

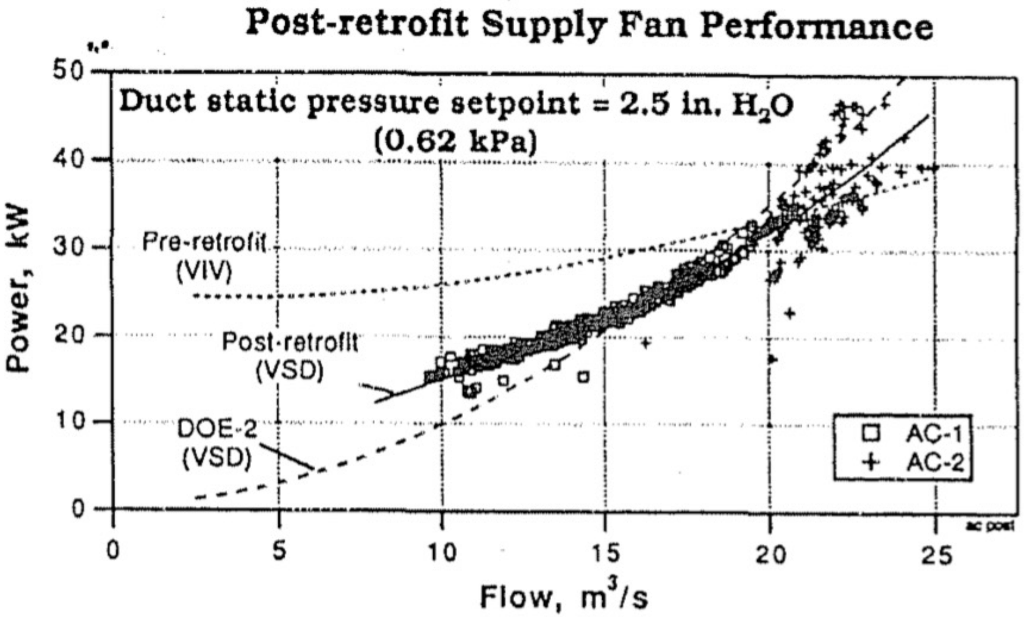
Greenheck, Double-Width Centrifugal Fan Performance Supplement https://content.greenheck.com/public/DAMProd/Original/10002/CentrifugalDWPerfSuppl_catalog.pdf

Validation
Nominal speed – comparison

Greenheck 13 BIDW

- Nominal speed
- *Hydraulic* efficiency and power
- Computed using Euler number
- Interpolated from fan curves





Post-retrofit Supply Fan Performance
Duct static pressure setpoint = 2.5 in. H2O
(0.62 kPa)
Power, kW
Flow, m3/s
Pre-retrofit
(VIV)
Post-retrofit
(VSD)
DOE-2
(VSD)
AC-1
AC-2
0
5
10
15
20
25
30
40
50

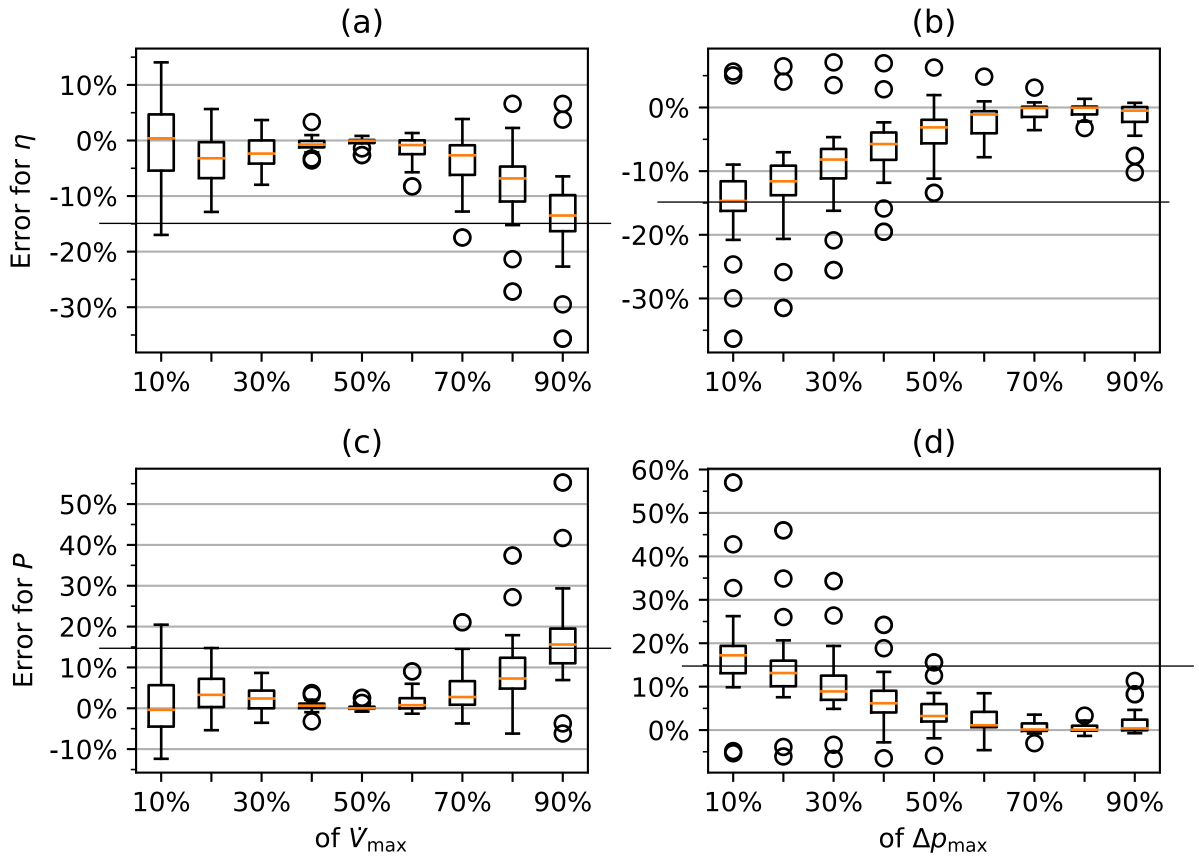
Validation
Nominal speed – error distributions

$$\text{Error} = \frac{\text{Computed} - \text{Interpolated}}{\text{Interpolated}}$$

Eighteen sets of pump data

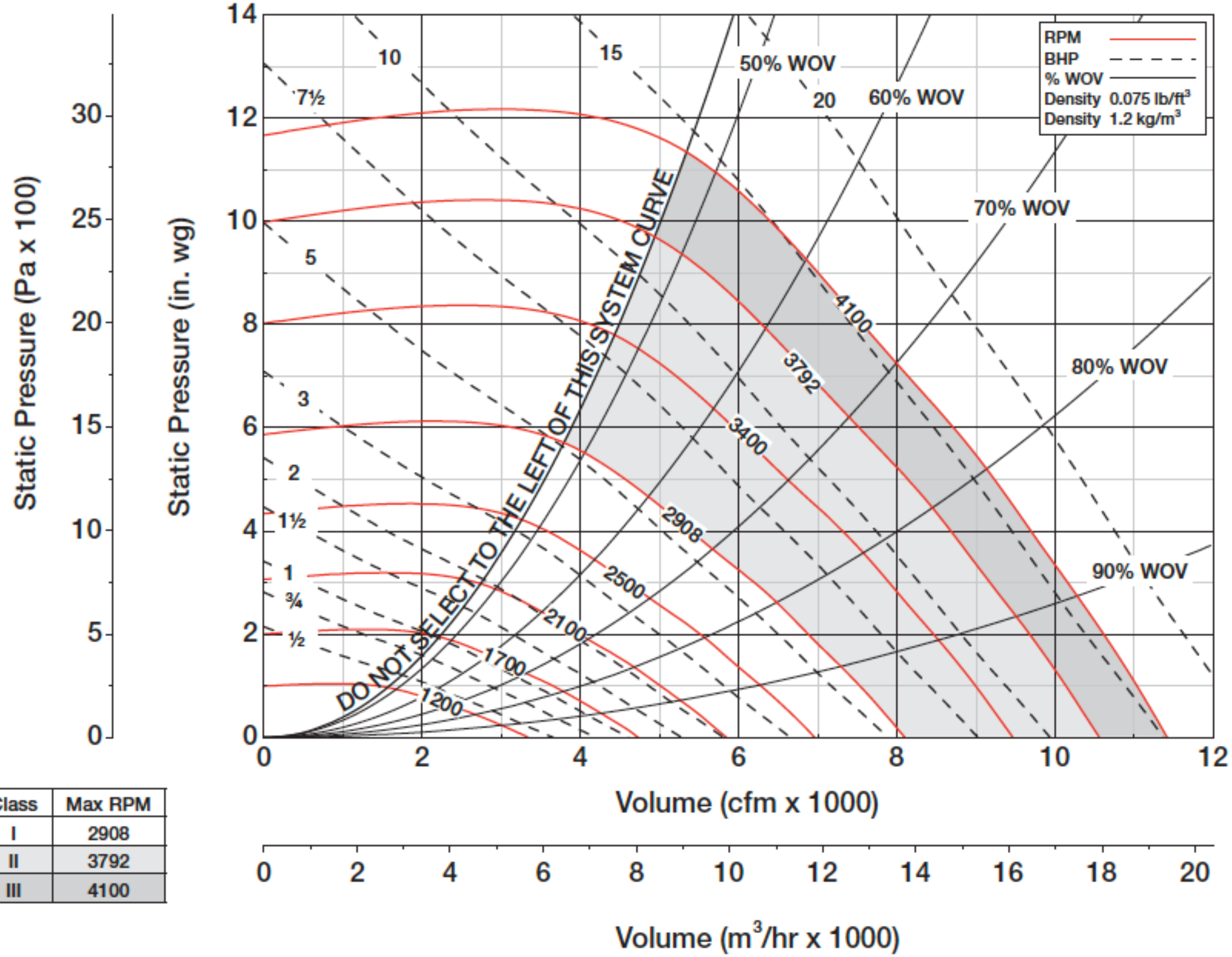
Seven sets of fan data

- The errors for computed power are within 15% for
  - 20% - 70% of max flow rate and
  - 40% - 90% of max pressure rise (excluding outliers).



13 BIDW

$$\frac{\eta}{\eta_p} = f\left(\frac{Eu}{Eu_p}\right)$$



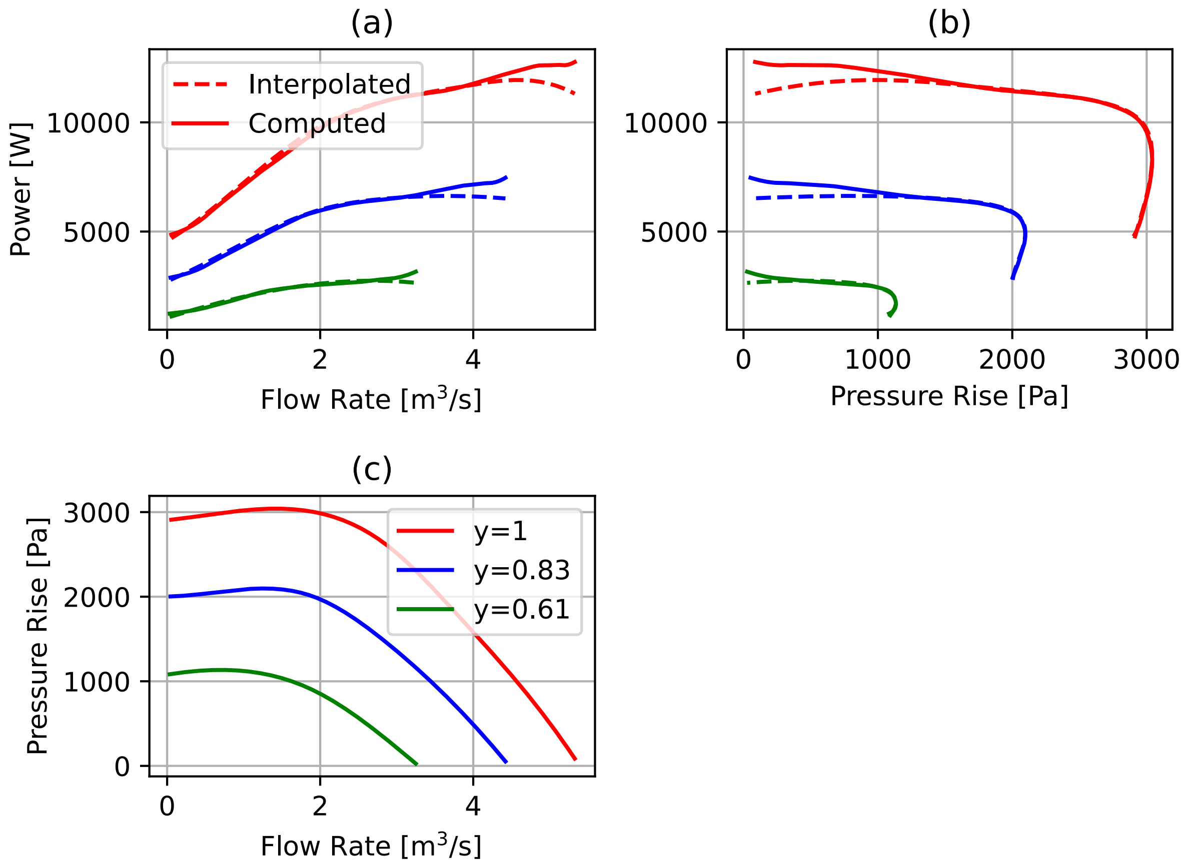
Class	Max RPM
I	2908
II	3792
III	4100

% WOV = (CFM X 100) / (RPM X 2.79)

Validation
Reduced speed

Greenheck 13 BIDW

- Nominal and reduced speeds
- *Hydraulic* efficiency and power
- Computed using Euler number
- Interpolated from fan curves



Validation
Reduced speed

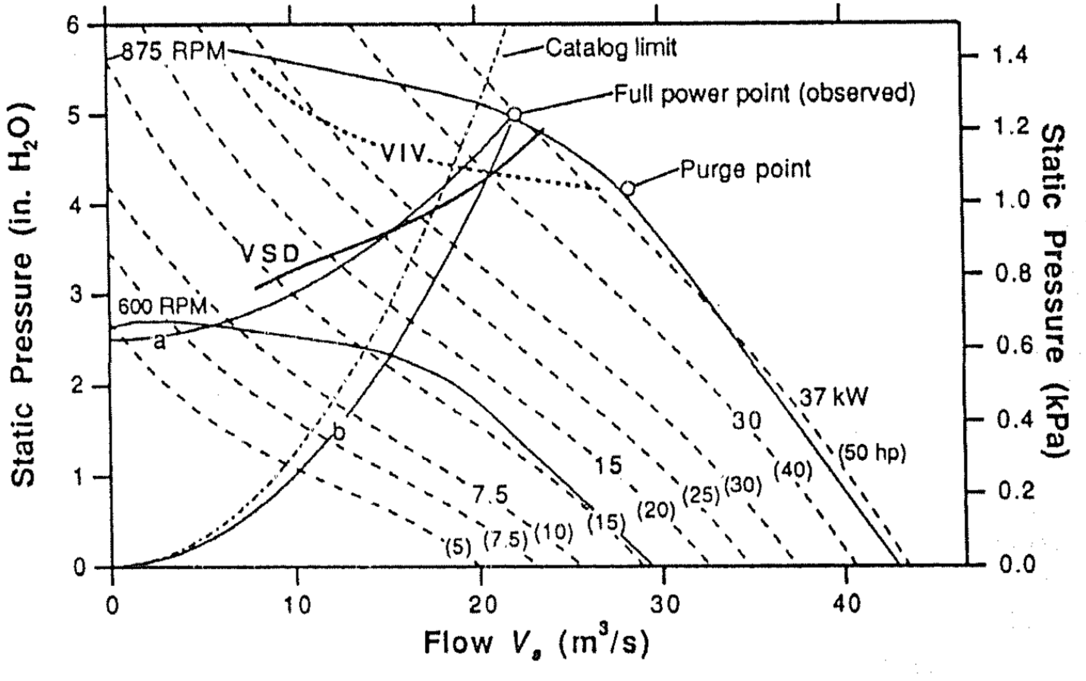
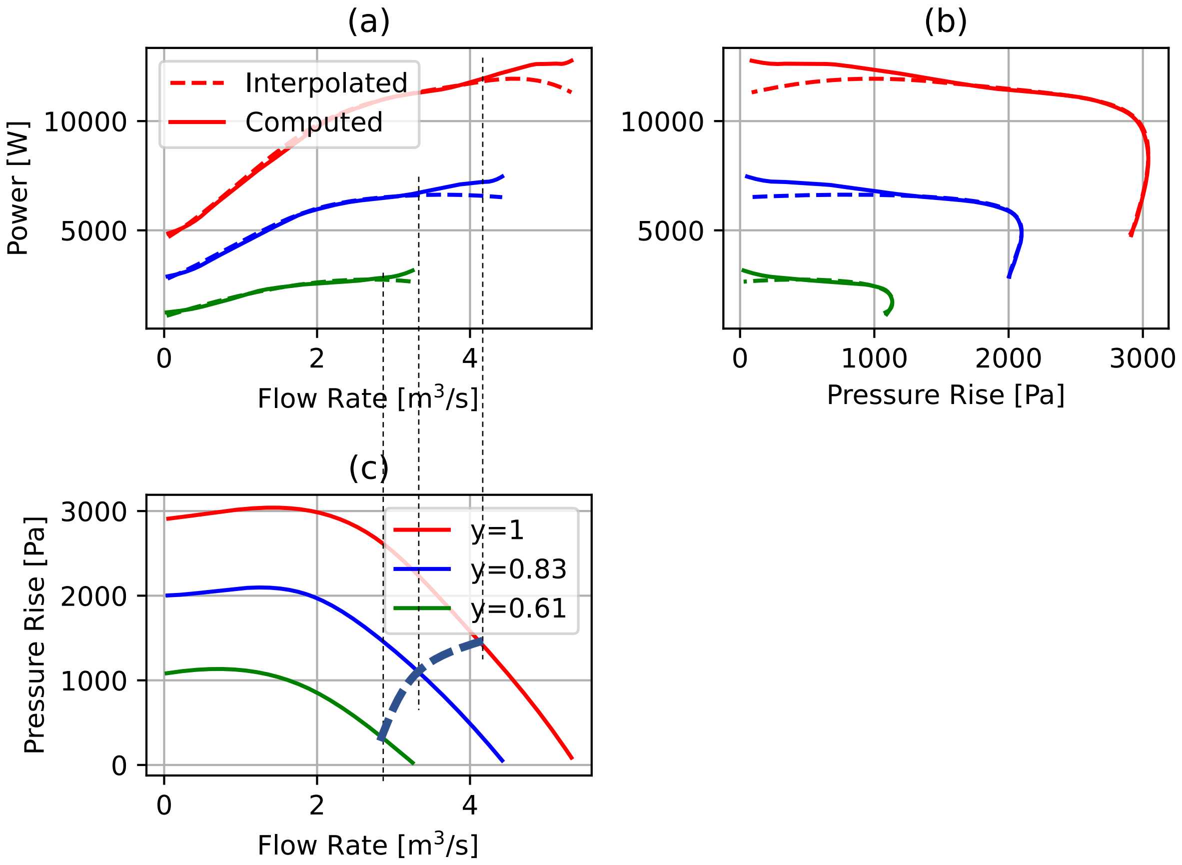


Figure 9

S.L. Englander and L.K. Norford (1992a). "Saving fan energy in VAV systems - part 1: Analysis of a variable speed drive retrofit." ASHRAE Transactions (98).

*not the same fan



Discussion

The correlation has the functional form

$$\frac{\eta}{\eta_p} = f\left(\log_{10}(Eu/Eu_p)\right) = f\left(\log_{10}\left(\frac{\Delta p}{\dot{V}^2}\frac{\dot{V}_p^2}{\Delta p_p}\right)\right)$$

Notice that $\dot{V}_p$ and Δp_p are constants.

The dependency can be further reduced to

$$\frac{\eta}{\eta_p} = g\left(\frac{\Delta p}{\dot{V}^2}\right)$$

Therefore, η is constant along any curve

$$\Delta p = k\,\dot{V}^2$$

Discussion

η is constant along any curve $\Delta p = k\,\dot{V}^2$

- The method does not reproduce efficiency degradation along constant system curves.
- In line with the simplification often used by fan manufacturers (Stein and Hydeman 2004; ASHRAE Standard 51-16).
- The method has the same accuracy as using manufacturer data (simplified).

ASHRAE (2016). *ASHRAE Standard 51-16 (ANSI/AMCA Standard 210-16), Laboratory Methods Of Testing Fans For Certified Aerodynamic Performance Rating.* ASHRAE.

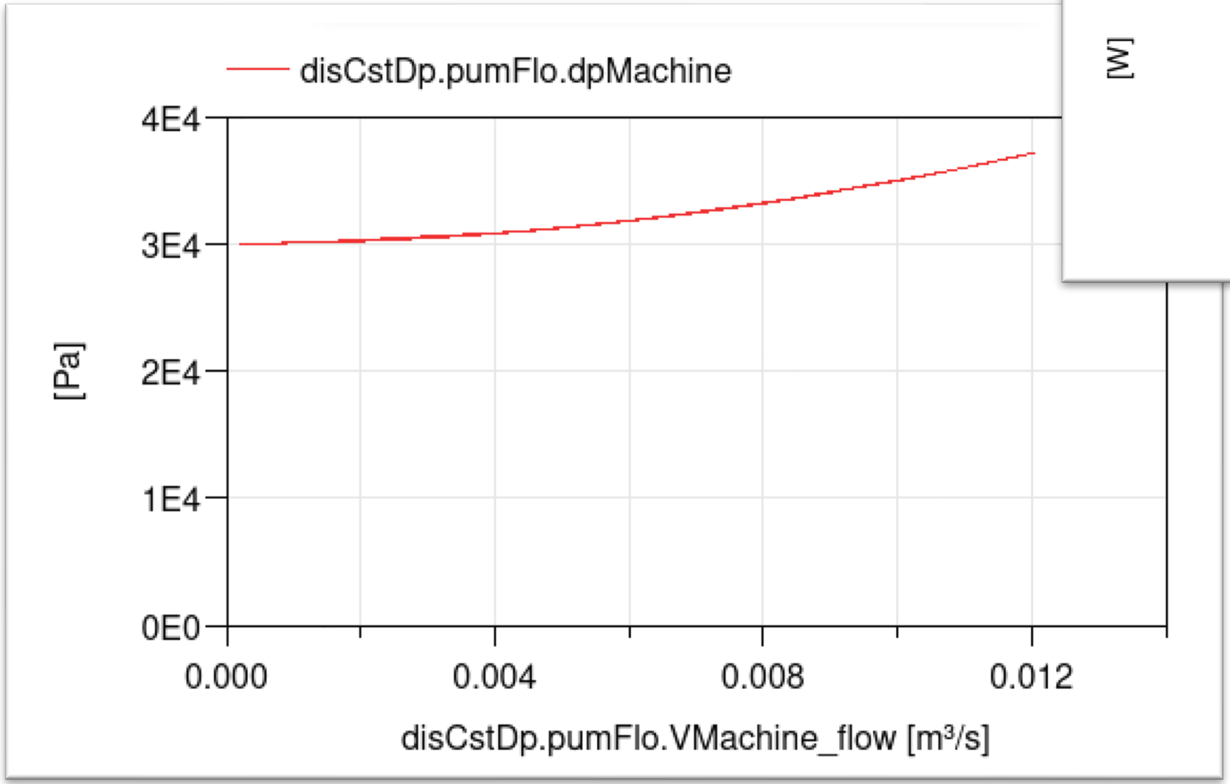
Stein, Jeff and Mark Hydeman (2004). "Development and Testing of the Characteristic Curve Fan Model." In: *ASHRAE transactions* 110.1.

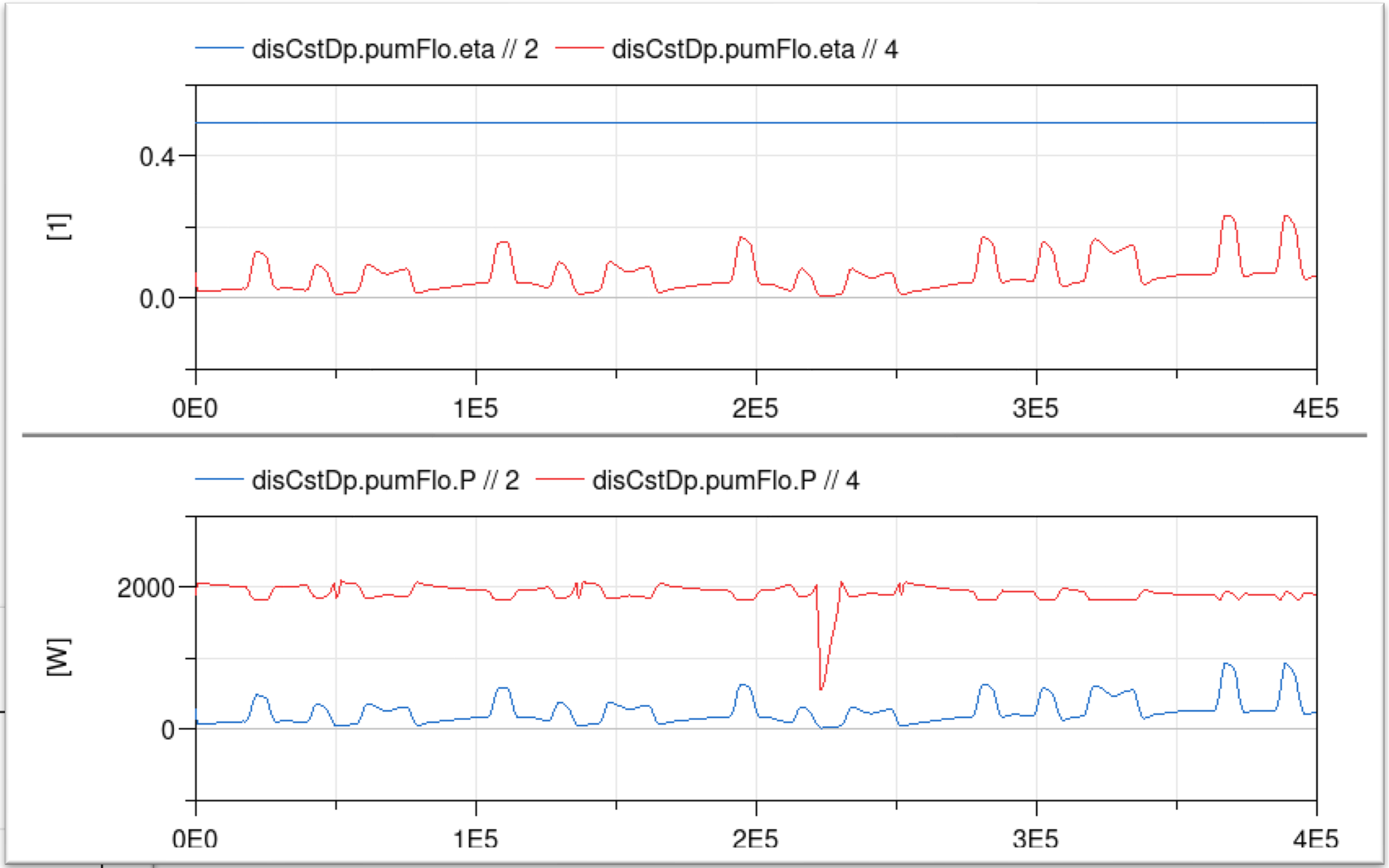
Example

```
Buildings.Experimental.DHC
.Loads.BaseClasses.Validation
.FlowDistributionPumpControl
```

2 = constant efficiency

4 = variable efficiency





Summary

- The method uses the Euler number & correlation to estimate the whole power/efficiency map of a fan (or pump).
- It only needs one data point (at peak efficiency) as user input.
- The computed power does not go to zero when the flow approaches zero
  - A more accurate representation of physics.
  - Useful for analysis in static reset applications, for example.
- At nominal speed, the computed power of the sample had errors within 15% for
  - 20% - 70% of max flow rate and
  - 40% - 90% of max pressure rise (excluding outliers).
- The accuracy drops considerably at low pressure & high flow rate, but this operating region is unusual for the type of applications that motivated this study.
- Otherwise, it has the same level of accuracy as using (simplified) manufacturer data.

- Thank you!

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