Fan and Pump Efficiency in Modelica Based on the Euler Number

American Modelica Conference
Building Energy 1
Wednesday, October 26, 2022

Hongxiang (Casper) Fu, David Blum, Michael Wetter
Building Technology and Urban Systems
Lawrence Berkeley National Laboratory, Berkeley, CA, USA
hcasperfu@lbl.gov, dhblum@lbl.gov, mwetter@lbl.gov
Acknowledgements

This research was supported by the Assistant Secretary for Efficiency and Renewable Energy, Office of Building Technologies of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

This work emerged from the IBPSA Project 1, an international project conducted under the umbrella of the International Building Performance Simulation Association (IBPSA). Project 1 will develop and demonstrate a BIM/GIS and Modelica Framework for building and community energy system design and operation.
Background

• Fan power from flow work

\[ \eta = \frac{W_{flo}}{P} = \frac{\dot{V} \cdot \Delta p}{P} \]

\[ P = \frac{W_{flo}}{\eta} = \frac{\dot{V} \cdot \Delta p}{\eta} \]

• \( \times \) \( P(\dot{V} \rightarrow 0, \eta = const) \rightarrow 0 \)

• \( \checkmark \) \( \eta(\dot{V} \rightarrow 0, P > 0) \rightarrow 0 \)

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”)

https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v9.4.0/EngineeringReference.pdf
Background

- Fan power from flow work

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

- \( \times \ P(\dot{V} \to 0, \eta = const) \to 0 \)
- \( \checkmark \ \eta(\dot{V} \to 0, P > 0) \to 0 \)

- Matters especially when:
  - \( \dot{V} \) is low, while
  - \( \Delta p \) is maintained at a certain level

Figure 5
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
    \[
    \frac{P}{P_d} = 0.0013 + 0.1470PLR + 0.9506PLR^2 - 0.0998PLR^3
    \]
    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)

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

https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v9.4.0/EngineeringReference.pdf
Methodology

Euler Number

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

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

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

\[ \frac{Eu}{Eu_p} = \frac{\Delta p \cdot V_p^2}{\dot{V}^2 \cdot \Delta p_p} \]

User input needed:

\( \eta_p, \Delta p_p, \dot{V}_p \)

* \( \eta \) 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)*
**Methodology**

**Euler Number**

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

where

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

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)*

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)

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

\[ P \frac{\eta_{mot}}{\eta_{hyd}} \frac{\eta_{hyd}}{\eta_{mot}} = \frac{\dot{W}_{hyd}}{P} \]

\[ P = \frac{\dot{V} \Delta p}{\eta_{hyd} \eta_{mot}} \]
Modelica Implementation
Efficiency and power items

\( \dot{W}_{\text{hyd}}(\dot{V}, \Delta p) \) and \( \eta_{\text{hyd}}(\dot{V}, \Delta p) \) 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 \( \log_{10} \left( \frac{E u}{E u_p} \right) \),

- 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

---

**Class** | **Max RPM**
--- | ---
I | 2908
II | 3792
III | 4100

\[
\% \text{ WOV} = \frac{(\text{CFM} \times 100)}{(\text{RPM} \times 2.79)}
\]

Greenheck, Double-Width Centrifugal Fan Performance Supplement
Validation
Nominal speed – comparison

Greenheck 13 BIDW
• Nominal speed
• *Hydraulic* efficiency and power
• Computed using Euler number
• Interpolated from fan curves
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).
\[ \frac{\eta}{\eta_p} = f \left( \frac{Eu}{Eu_p} \right) \]
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
Discussion

The correlation has the functional form
\[
\frac{\eta}{\eta_p} = f \left( \log_{10} \left( \frac{Eu}{Eu_p} \right) \right) = f \left( \log_{10} \left( \frac{\Delta p \, \dot{V}_p^2}{\dot{V}^2 \, \Delta p_p} \right) \right)
\]

Notice that \( \dot{V}_p \) and \( \Delta p_p \) are constants.

The dependency can be further reduced to
\[
\frac{\eta}{\eta_p} = g \left( \frac{\Delta p}{\dot{V}^2} \right)
\]

Therefore, \( \eta \) is constant along any curve
\[
\Delta p = k \, \dot{V}^2
\]
Discussion

η is constant along any curve Δp = 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).


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!

H. (Casper) Fu, Ph.D.
Postdoctoral Researcher,
Lawrence Berkeley National Laboratory
HCFasperFu@lbl.gov

Hongxiang (Casper) Fu, David Blum, Michael Wetter
Building Technology and Urban Systems
Lawrence Berkeley National Laboratory, Berkeley, CA, USA
hcasperfu@lbl.gov, dhblum@lbl.gov, mwetter@lbl.gov