$Bhp_{New} = Bhp_{Old} \times \left(\frac{Flow_{New}}{Flow_{Old}}\right)^{\prime}$ Where:

Pressure<sub>New</sub> = The pressure you want to know in consistent units Pressure<sub>Old</sub> = The pressure you know in consistent units

Flow\_New = The pressure you want to know in consistent units

Flow<sub>Old</sub> = The pressure you want to know in consistent units

 $\eta = 3$  for a true fixed system with a single system curve that goes through the origin at 0 f.t.w.c and 0 gpm. For variable flow systems, which operate on a range of system curves, this is an expontent selected to approximate the impact of variable flow plant operation, fixed pressure set points, and other operational factors to allow the affinity law to predict pump or fan power.

Note that the relationship can be applied using kW or any other power metric as long as you keep the units consistent. In other words:

$$kW_{New} = kW_{Old} \times \left(\frac{Flow_{New}}{Flow_{Old}}\right)$$

The exponent will be dependent on the specific nature of the system in terms of the control pressure that is maintained relative to the design pressure, the location of the controlling sensor, the ratio of distribution main losses to losses through the branches to the loads and similar factors. You can develop one for a particular system based on an analysis for limiting conditions and specific operating conditions.

Alternatively, you can use an exponent cited from a credible source like a University, and organization like ASHRAE, or supporting technical information from a utility incentive program. One example of suggested exponents for HVAC fan and pump systems was published by Southern California Edison in a document titled *Fan and Pump Affinity Law Clarification*. The exponents below are from that publication and are intended to be used as guidelines.

Engineering judgement can be used to modify them slightly based on the specific operating conditions for a specific system or to come up with similar coefficients based on a more rigorous analysis of the system. Definitions of open, closed, fixed and variable systems follow the exponent list.

Closed, fixed water systems:  $\eta = 2.4$ Open, fixed water systems:  $\eta = 2.2$ 

Fixed air systems serving enclosures like CRAC units serving enclosed hot or cold aisles;  $\eta = 2.2$ Fixed air systems serving enclosures like CRAC units serving open plenums;  $\eta = 2.0$ 

Variable air or water systems with a fixed pressure control set point

Fixed set point is 20% or less of the total pressure required at design flow;  $\eta = 2.4$ Fixed set point is 20% - 50% of the total pressure required at design flow;  $\eta = 2.0$ Fixed set point is 50% - 80% of the total pressure required at design flow;  $\eta = 1.5$ Fixed set point is greater than 80% of the total pressure required at design flow;  $\eta = 1.0$ 

Variable air or water systems with a variable pressure control set point;  $\eta$  = 2.4



## Notes:

1. The "Square Law" defining the system flow versus pressure drop relationship for a piping or duct system with fully developed turbulent flow. It is also the exponent recommended by Southern California Edison to adjust the "Cube Rule" for:

a. A constant volume air system serving open plenums.

- b. A variable flow air or water system with a fixed set point that is 20% 50% of the total pressure required at design flow.
- 2. The ASHRAE research based system curve relationship for typical HVAC systems due to the fact that in some parts of the system, there is not fully developed turbulent flow.
- 3. The "Cube Rule" or Affinity Law defining the relationship between pump or fan power and flow or speed.
- 4. Southern California Edison's suggested affinity law exponent for:
  - a. A closed constant volume water system.
  - b. A variable flow air or water system with a fixed set point that is 20% or less of the total pressure required at design flow.
  - c. A variable flow air or water system with a reset set point.
- 5. Southern California Edison's suggested affinity law exponent for:
  - a. An open constant volume water system.
  - b. A constant volume air system like a CRAC (Computer Room Air Conditioning) unit serving enclosed hot or cold aisles.
- 6. Southern California Edison's suggested affinity law exponent for a variable flow air or water system with a fixed set point that is 50% 80% of the total pressure required at design flow.
- 7. The equation of a straight line and also Southern California Edison's suggested affinity law exponent for a variable flow air or water system with a fixed set point that is greater than 80% of the total pressure required at









| System Curve Points |       |          |
|---------------------|-------|----------|
| Condition           | Flow  | Pressure |
| 140% of known flow  | 1,820 | 137.20   |
| 120% of known flow  | 1,560 | 100.80   |
| Known               | 1,300 | 70.00    |
| 80% of known flow   | 1,040 | 44.80    |
| 60% of known flow   | 780   | 25.20    |
| 40% of known flow   | 520   | 11.20    |
| 30% of known flow   | 390   | 6.30     |
| 20% of known flow   | 260   | 2.80     |
| 18% of known flow   | 234   | 2.27     |
| 16% of known flow   | 208   | 1.79     |
| 14% of known flow   | 182   | 1.37     |
| 12% of known flow   | 156   | 1.01     |
| 10% of known flow   | 130   | 0.70     |
| 8% of known flow    | 104   | 0.45     |
| 6% of known flow    | 78    | 0.25     |
| 4% of known flow    | 31    | 0.04     |
| 2% of known flow    | 16    | 0.01     |
| No Flow             | 0     | 0.00     |

$$Pressure_{New} = Pressure_{Old} \times \left(\frac{Flow_{New}}{Flow_{Old}}\right)$$

Where:



| Summary   |            |              |             |            |          |            |            |              |             |                     |                     |                     |                     |
|-----------|------------|--------------|-------------|------------|----------|------------|------------|--------------|-------------|---------------------|---------------------|---------------------|---------------------|
| Load      | Flow Rate, | Head, ft.w.c | Pump Speed, | Pump       | Pump Bhp | Motor      | VFD        | Projected kW | "Cube Rule" | kW vs.              | kW vs.              | kW vs.              | Head vs.            |
| Condition | gpm        |              | rpm         | Efficiency |          | Efficiency | Efficiency |              | kW          | Flow <sup>2.4</sup> | Flow <sup>2.0</sup> | Flow <sup>1.5</sup> | Flow <sup>2.0</sup> |
| Design    | 1,300.0    | 70.000       | 1,150       | 86.9%      | 26.4     | 94%        | 98%        | 28.8         | 28.8        | 28.8                | 28.8                | 28.8                | 70.0                |





![](_page_9_Figure_0.jpeg)

| System Curve Points |       |          |
|---------------------|-------|----------|
| Condition           | Flow  | Pressure |
| 160% of known flow  | 1,560 | 134.40   |
| 120% of known flow  | 1,170 | 75.60    |
| Known               | 975   | 52,50    |
| 80% of known flow   | 780   | 33.60    |
| 60% of known flow   | 585   | 18.90    |
| 40% of known flow   | 390   | 8.40     |
| 30% of known flow   | 293   | 4.73     |
| 20% of known flow   | 195   | 2.10     |
| 18% of known flow   | 176   | 1.70     |
| 16% of known flow   | 156   | 1.34     |
| 14% of known flow   | 137   | 1.03     |
| 12% of known flow   | 117   | 0.76     |
| 10% of known flow   | 98    | 0.53     |
| 8% of known flow    | 78    | 0.34     |
| 6% of known flow    | 59    | 0.19     |
| 4% of known flow    | 23    | 0.03     |
| 2% of known flow    | 12    | 0.01     |
| No Flow             | 0     | 0.00     |

$$\mathsf{Pressure}_{\mathsf{New}} = \mathsf{Pressure}_{\mathsf{Old}} \times \left(\frac{\mathsf{Flow}_{\mathsf{New}}}{\mathsf{Flow}_{\mathsf{Old}}}\right)$$

Where:

![](_page_10_Figure_4.jpeg)

| System Curve Points |       |          |
|---------------------|-------|----------|
| Condition           | Flow  | Pressure |
| 160% of known flow  | 1,560 | 134.40   |
| 120% of known flow  | 1,170 | 75.60    |
| Known               | 975   | 52,50    |
| 80% of known flow   | 780   | 33.60    |
| 60% of known flow   | 585   | 18.90    |
| 40% of known flow   | 390   | 8.40     |
| 30% of known flow   | 293   | 4.73     |
| 20% of known flow   | 195   | 2.10     |
| 18% of known flow   | 176   | 1.70     |
| 16% of known flow   | 156   | 1.34     |
| 14% of known flow   | 137   | 1.03     |
| 12% of known flow   | 117   | 0.76     |
| 10% of known flow   | 98    | 0.53     |
| 8% of known flow    | 78    | 0.34     |
| 6% of known flow    | 59    | 0.19     |
| 4% of known flow    | 23    | 0.03     |
| 2% of known flow    | 12    | 0.01     |
| No Flow             | 0     | 0.00     |

![](_page_11_Figure_1.jpeg)

| Speed projection from the 75 | % System Curve                   |
|------------------------------|----------------------------------|
| Desired Flow -               | 975 gpm(given)                   |
| Known flow -                 | 1,150 gpm (from75% system curve) |
| Known impeller speed -       | 1,150 rpm (rated speed)          |
| "Tweak" value -              | -25 rpm (Manual ajustment)       |
| Desired impeller speed -     | 950 rpm                          |

![](_page_12_Figure_1.jpeg)

- *Flow<sub>New</sub>* = The flow rate you are trying to predict in consistent units
- *Flow<sub>Old</sub>* = The flow rate you know in consistent units
- Speed<sub>New</sub> = The rated impeller speed used for the original curve in consistent units  $Speed_{Old}$  = The new impeller speed at the test condition in consistent units

Solving this for Speed<sub>New</sub> yields:

 $\left(\frac{\textit{Flow}_{\textit{New}}}{\textit{Flow}_{\textit{Old}}}\right) \times \textit{Speed}_{\textit{Old}} = \textit{Speed}_{\textit{New}}$ 

![](_page_12_Figure_7.jpeg)

| Summary   |            |              |             |            |          |            |            |              |             |                     |                     |                     |                     |
|-----------|------------|--------------|-------------|------------|----------|------------|------------|--------------|-------------|---------------------|---------------------|---------------------|---------------------|
| Load      | Flow Rate, | Head, ft.w.c | Pump Speed, | Pump       | Pump Bhp | Motor      | VFD        | Projected kW | "Cube Rule" | kW vs.              | kW vs.              | kW vs.              | Head vs.            |
| Condition | gpm        |              | rpm         | Efficiency |          | Efficiency | Efficiency |              | kW          | Flow <sup>2.4</sup> | Flow <sup>2.0</sup> | Flow <sup>1.5</sup> | Flow <sup>2.0</sup> |
| Design    | 1,300.0    | 70.000       | 1,150       | 86.9%      | 26.4     | 94%        | 98%        | 28.8         | 28.8        | 28.8                | 28.8                | 28.8                | 70.0                |
| 75.0%     | 975.0      | 52.500       | 950         | 86.1%      | 15.0     | 94%        | 94%        | 17.0         | 12.2        | 14.4                | 16.2                | 18.7                | 52.5                |

 $hp = \left(\frac{Flow_{gpm} \times Head_{ft.w.c.}}{3,960 \times \eta_{Pump} \times \eta_{Motor} \times \eta_{VSD}}\right)$ 

![](_page_14_Figure_0.jpeg)

| Summary   |            |              |             |            |          |            |            |              |             |                     |                     |                     |                     |
|-----------|------------|--------------|-------------|------------|----------|------------|------------|--------------|-------------|---------------------|---------------------|---------------------|---------------------|
| Load      | Flow Rate, | Head, ft.w.c | Pump Speed, | Pump       | Pump Bhp | Motor      | VFD        | Projected kW | "Cube Rule" | kW vs.              | kW vs.              | kW vs.              | Head vs.            |
| Condition | gpm        |              | rpm         | Efficiency |          | Efficiency | Efficiency |              | kW          | Flow <sup>2.4</sup> | Flow <sup>2.0</sup> | Flow <sup>1.5</sup> | Flow <sup>2.0</sup> |
| Design    | 1,300.0    | 70.000       | 1,150       | 86.9%      | 26.4     | 94%        | 98%        | 28.8         | 28.8        | 28.8                | 28.8                | 28.8                | 70.0                |
| 75.0%     | 975.0      | 52.500       | 950         | 86.1%      | 15.0     | 94%        | 94%        | 17.0         | 12.2        | 14.4                | 16.2                | 18.7                | 52.5                |
| 50.0%     | 650.0      | 40.000       | 810         | 81.3%      | 8.1      | 93%        | 94%        | 9.3          | 3.6         | 5.5                 | 7.2                 | 10.2                | 40.0                |

$$hp = \left(\frac{Flow_{gpm} \times Head_{ft.w.c.}}{3,960 \times \eta_{Pump} \times \eta_{Motor} \times \eta_{VSD}}\right)$$

![](_page_16_Figure_0.jpeg)

| Summary   | Summary    |              |             |            |          |            |            |              |             |                     |                     |                     |                     |  |
|-----------|------------|--------------|-------------|------------|----------|------------|------------|--------------|-------------|---------------------|---------------------|---------------------|---------------------|--|
| Load      | Flow Rate, | Head, ft.w.c | Pump Speed, | Pump       | Pump Bhp | Motor      | VFD        | Projected kW | "Cube Rule" | kW vs.              | kW vs.              | kW vs.              | Head vs.            |  |
| Condition | gpm        |              | rpm         | Efficiency |          | Efficiency | Efficiency |              | kW          | Flow <sup>2.4</sup> | Flow <sup>2.0</sup> | Flow <sup>1.5</sup> | Flow <sup>2.0</sup> |  |
| Design    | 1,300.0    | 70.000       | 1,150       | 86.9%      | 26.4     | 94%        | 98%        | 28.8         | 28.8        | 28.8                | 28.8                | 28.8                | 70.0                |  |
| 75.0%     | 975.0      | 52.500       | 950         | 86.1%      | 15.0     | 94%        | 94%        | 17.0         | 12.2        | 14.4                | 16.2                | 18.7                | 52.5                |  |
| 50.0%     | 650.0      | 40.000       | 810         | 81.3%      | 8.1      | 93%        | 94%        | 9.3          | 3.6         | 5.5                 | 7.2                 | 10.2                | 40.0                |  |
| 25.0%     | 325.0      | 32.500       | 723         | 64.0%      | 4.2      | 87%        | 88%        | 5.5          | 0.5         | 1.0                 | 1.8                 | 3.6                 | 32.5                |  |

![](_page_17_Figure_1.jpeg)

![](_page_18_Figure_0.jpeg)

| Summary   |            |              |             |            |          |            |            |              |             |                     |                     |                     |                     |
|-----------|------------|--------------|-------------|------------|----------|------------|------------|--------------|-------------|---------------------|---------------------|---------------------|---------------------|
| Load      | Flow Rate, | Head, ft.w.c | Pump Speed, | Pump       | Pump Bhp | Motor      | VFD        | Projected kW | "Cube Rule" | kW vs.              | kW vs.              | kW vs.              | Head vs.            |
| Condition | gpm        |              | rpm         | Efficiency |          | Efficiency | Efficiency |              | kW          | Flow <sup>2.4</sup> | Flow <sup>2.0</sup> | Flow <sup>1.5</sup> | Flow <sup>2.0</sup> |
| Design    | 1,300.0    | 70.000       | 1,150       | 86.9%      | 26.4     | 94%        | 98%        | 28.8         | 28.8        | 28.8                | 28.8                | 28.8                | 70.0                |
| 75.0%     | 975.0      | 52.500       | 950         | 86.1%      | 15.0     | 94%        | 94%        | 17.0         | 12.2        | 14.4                | 16.2                | 18.7                | 52.5                |
| 50.0%     | 650.0      | 40.000       | 810         | 81.3%      | 8.1      | 93%        | 94%        | 9.3          | 3.6         | 5.5                 | 7.2                 | 10.2                | 40.0                |
| 25.0%     | 325.0      | 32.500       | 723         | 64.0%      | 4.2      | 87%        | 88%        | 5.5          | 0.5         | 1.0                 | 1.8                 | 3.6                 | 32.5                |
| 12.5%     | 162.5      | 30.625       | 694         | 40.0%      | 3.1      | 84%        | 84%        | 4.5          | 0.1         | 0.2                 | 0.5                 | 1.3                 | 30.6                |

$$hp = \left(\frac{Flow_{gpm} \times Head_{ft.w.c.}}{3,960 \times \eta_{Pump} \times \eta_{Motor} \times \eta_{VSD}}\right)$$

| Summary   |            |              |             |            |          |            |            |              |             |                     |                     |                     |                     |
|-----------|------------|--------------|-------------|------------|----------|------------|------------|--------------|-------------|---------------------|---------------------|---------------------|---------------------|
| Load      | Flow Rate, | Head, ft.w.c | Pump Speed, | Pump       | Pump Bhp | Motor      | VFD        | Projected kW | "Cube Rule" | kW vs.              | kW vs.              | kW vs.              | Head vs.            |
| Condition | gpm        |              | rpm         | Efficiency |          | Efficiency | Efficiency |              | kW          | Flow <sup>2.4</sup> | Flow <sup>2.0</sup> | Flow <sup>1.5</sup> | Flow <sup>2.0</sup> |
| Design    | 1,300.0    | 70.000       | 1,150       | 86.9%      | 26.4     | 94%        | 98%        | 28.8         | 28.8        | 28.8                | 28.8                | 28.8                | 70.0                |
| 75.0%     | 975.0      | 52.500       | 950         | 86.1%      | 15.0     | 94%        | 94%        | 17.0         | 12.2        | 14.4                | 16.2                | 18.7                | 52.5                |
| 50.0%     | 650.0      | 40.000       | 810         | 81.3%      | 8.1      | 93%        | 94%        | 9.3          | 3.6         | 5.5                 | 7.2                 | 10.2                | 40.0                |
| 25.0%     | 325.0      | 32.500       | 723         | 64.0%      | 4.2      | 87%        | 88%        | 5.5          | 0.5         | 1.0                 | 1.8                 | 3.6                 | 32.5                |
| 12.5%     | 162.5      | 30.625       | 694         | 40.0%      | 3.1      | 84%        | 84%        | 4.5          | 0.1         | 0.2                 | 0.5                 | 1.3                 | 30.6                |

![](_page_20_Figure_1.jpeg)

Head vs. Flow

![](_page_20_Figure_3.jpeg)

![](_page_20_Figure_4.jpeg)

|   | Summary   |            |              |             |            |          |            |            |              |             |                   |
|---|-----------|------------|--------------|-------------|------------|----------|------------|------------|--------------|-------------|-------------------|
|   | Load      | Flow Rate, | Head, ft.w.c | Pump Speed, | Pump       | Pump Bhp | Motor      | VFD        | Projected kW | "Cube Rule" | kW v              |
|   | Condition | gpm        |              | rpm         | Efficiency |          | Efficiency | Efficiency |              | kW          | Flow <sup>2</sup> |
|   | Design    | 1,300.0    | 70.000       | 1,150       | 86.9%      | 26.4     | 94%        | 98%        | 28.8         | 28.8        | 28.8              |
|   | 75.0%     | 975.0      | 70.000       | 1,081       | 83.5%      | 20.6     | 94%        | 96%        | 23.0         | 12.2        | 14.4              |
|   | 50.0%     | 650.0      | 70.000       | 1,063       | 72.0%      | 16.0     | 94%        | 94%        | 18.1         | 3.6         | 5.5               |
|   | 25.0%     | 325.0      | 70.000       | 1,055       | 50.0%      | 11.5     | 94%        | 95%        | 12.9         | 0.5         | 1.0               |
|   | 12.5%     | 162.5      | 70.000       | 1,054       | 30.0%      | 9.6      | 93%        | 95%        | 10.8         | 0.1         | 0.2               |
| 1 |           |            |              |             |            |          |            |            |              |             |                   |

![](_page_21_Figure_1.jpeg)

Head vs. Flow

200

----- Head vs. Flow

400

![](_page_21_Figure_3.jpeg)

## Summary and Comparison of Different Methods of Optimizing the Chiller Plant Model Distribution Pumps

![](_page_22_Figure_1.jpeg)

| Comparison with the Original Configuration (1510 5A, Discharge Sensor) |           |          |              |          |                |      |  |  |  |  |  |  |
|--|-----------|----------|--------------|----------|----------------|------|--|--|--|--|--|--|
| Option   |           | Savings  |              | Cost     | Simple         | Note |  |  |  |  |  |  |
|  | kWh       | \$       | % of Maximum |          | Payback, Years |      |  |  |  |  |  |  |
| 1510 5A, Discharge Sensor  | Base Case |          |              |          |                |      |  |  |  |  |  |  |
| 1510 5A, Remote Sensor   | 27,070    | \$4,873  | 38%          | \$4,350  | 0.9            | 2    |  |  |  |  |  |  |
| 1510 5A, Trim and Respond  | 70,389    | \$12,670 | 100%         | \$7,254  | 0.6            | 3    |  |  |  |  |  |  |
| 1510 5E, Remote Sensor   | 57,806    | \$10,405 | 82%          | \$97,116 | 9.3            | 4    |  |  |  |  |  |  |
| Notes  |           |          |              |          | ·              |      |  |  |  |  |  |  |

- differential pressure between the pump headers in the central plant.
- chilled water valve nearly fully open.
- remote location in the system.

1. The base case has a relatively inefficient pump operating with its speed controlled based on the

2. This options adds a sensor at a remote point in the system which is used to reset the set point of the discharge pressure control process based on the differential pressure at the remote location.

3. This option uses a trim and repond strategy to reset the discharge pressure control process set point. The trim and respond process steps the set point up and down in an effort to keep at least one AHU

4. This option replaces the existing pump with a new pump that is 13% more efficient and then controlls it based on discharge pressure with the set point reset based on the differential pressure at a