Hot Water Boiler Performance Calculations

FAQ: How does HAP calculate energy performance for a fuel-fired hot water boiler?

ANSWER: HAP provides four different modeling options for calculating fuel-fired hot water boiler performance in energy simulations. In separate sections below the basic boiler energy input rate calculation and the specific efficiency calculations for the four modeling options will be described. Note that this discussion focuses only on performance of a single boiler for a given set of hourly load and hot water supply temperature operating conditions. Calculation for the hot water plant operation as a whole is a larger subject which is outside the scope of this article.

A. Boiler Energy Input Rate

Regardless of the modeling option used, the boiler input energy rate is calculated as follows:

$$Q_{input} = (Q_{load} / \eta_{boiler}) \times R_{cycle}$$

where:

Q_{input} = Energy input rate for boiler, MBH

Q_{load} = Boiler load, MBH

η_{boiler} = Boiler efficiency, decimal.

R_{cycle} = Cycling ratio, decimal. This is the fraction of the hour the boiler is cycled on. This applies when the boiler part load ratio is less than 10%, in which case the boiler is assumed to be operating at 10% load and cycling on and off to match demand. Above 10% part-load the boiler operates continuously and the cycling ratio is 1.0.

What differs between the four modeling options is how the boiler efficiency, η_{boiler}, is calculated.

B. Constant Efficiency Model

This is a simplified model in which the "overall efficiency" specified for the boiler is used for all operating hours. Therefore performance is represented by a constant efficiency and is not affected by the part-load ratio or hot water supply temperature for the current hour. For each hour the boiler efficiency is:

$$\eta_{boiler} = \eta_{constant}$$

where:

$\eta_{constant}$ = Constant "overall efficiency" specified by user.

Because a constant efficiency is used, and part-load ratio is not considered, the cycling ratio is always set to 1.0 for this boiler model.

Example: Constant Efficiency Model

Given: The boiler overall efficiency is 75%. For the current hour the boiler load is 370 MBH

Solution: Input energy rate for the hour is:

$$Q_{input} = (Q_{load} / \eta_{boiler}) \times R_{cycle}$$

$$Q_{input} = (370 / 0.75) \times 1.0 = 493.3 \text{ MBH}$$

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B. User Defined Curve: Efficiency = f(PLR)

This is a simplified model in which the user defines a table of boiler efficiencies at 10% steps of part-load ratio from 100% to 10% to define boiler performance. Therefore boiler performance is only analyzed as a function of part-load ratio. Other factors such as hot water supply temperature are not considered.

Efficiency calculations for this modeling option are as follows:

PLR = larger of { Q_{load} / Q_{cap} or 0.10}

where:

PLR   =   Boiler part load ratio, decimal.
Q_{load} =   Boiler load, MBH
Q_{cap} =   Boiler design capacity, MBH
0.10   =   The minimum unloading point is assumed to be 10% of design capacity. If the ratio of load to capacity is less than 10%, the boiler will operate at 10% capacity but will cycle on and off during the hour to meet the heating demand.

Cycling ratio is calculated as:

R_{cycle} = 1.0   if PLR > 0.10

R_{cycle} = (Q_{load} / Q_{cap}) / (0.10) if PLR = 0.10

Finally, the boiler efficiency, η_{boiler}, is calculated by linear interpolation between adjacent values in the user-defined boiler efficiency curve. For example, if PLR is 0.74, the program will interpolate between the efficiencies defined at 80% and 70% load in the efficiency curve table.

Example: User Defined Curve Model

Given:

The boiler design capacity is 500 MBH.

The efficiency curve specifies an efficiency of 77% at 80% load and 73% efficiency at 70% load.

For the current hour the boiler load is 370 MBH.

Solution:

PLR = Q_{load} / Q_{cap} = 370 / 500 = 0.74

R_{cycle} = 1.0 since PLR is ≥ 0.10

η_{boiler} = 0.746 This is the efficiency at 74% load, interpolated between the given 80% and 70% load points.

Q_{input} = (Q_{load} / η_{boiler}) x R_{cycle}

Q_{input} = (370 / 0.746) x 1.0 = 496.0 MBH

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C. Non-Condensing Boiler: Efficiency = f(PLR, HWST)

With this option HAP uses a curve fit performance model which adapts the U.S. Department of Energy (DOE) EnergyPlus curve fit representing a non-condensing boiler. This is a 2-dimensional model in which performance is a function of both part-load ratio and hot water supply temperature (HWST).

Efficiency calculations for this modeling option are as follows:

PLR = larger of { Q_{load} / Q_{cap} or 0.10}

where:

PLR	=	Boiler part load ratio, decimal.
Q_{load}	=	Boiler load, MBH
Q_{cap}	=	Boiler design capacity, MBH
0.10	=	The minimum unloading point is assumed to be 10% of design capacity. If the ratio of load to capacity is less than 10%, the boiler will operate at 10% capacity but will cycle on and off during the hour to meet the heating demand.

Cycling ratio is calculated as:

R_{cycle} = 1.0   if PLR > 0.10

R_{cycle} = (Q_{load} / Q_{cap}) / (0.10) if PLR = 0.10

Boiler efficiency is calculated as:

η_{boiler} = (η_{design}) (F_{boiler}) / (F_{design})

where:

η_{boiler}	=	Efficiency of boiler at given PLR and hot water supply temperature operating conditions, decimal.
η_{design}	=	Efficiency of boiler at rated capacity, decimal. This value is specified by the user.
F_{boiler}	=	Boiler efficiency correction factor, decimal. This factor accounts for changes in efficiency between the design condition and the current hour's part-load and off-design HWST conditions. This curve is obtained from EnergyPlus.
	=	1.111720116 $+ 0.078614078\,(PLR)$ $- 0.400425756\,(PLR)^2$ $- 0.000156783\,(HWST_c)^2$ $+ 0.009384599\,(PLR)\,(HWST_c)$ $+ 0.234257955\,(PLR)^3$ $+ 0.00000132927\,(HWST_c)^3$ $- 0.004446701\,(PLR)^2\,(HWST_c)$ $- 0.0000122498\,(PLR)\,(HWST_c)^2$
F_{design}	=	Boiler efficiency design correction factor, decimal. This factor corrects for the fact the EnergyPlus non-condensing boiler curve represents a boiler at a specific design hot water supply temperature condition. To apply the curve at other design hot water supply temperatures, the curve must be corrected. F_{design} is calculated using the equation above for F_{boiler} using input values of PLR =1.0 and $HWST_c$ = design supply hot water temperature for the boiler being modeled.
$HWST_c$	=	Hot water supply temperature delivered by the boiler, converted to degrees Celsius. The temperature in deg C is required because that was the basis for the EnergyPlus curve fit.

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Example: Non-Condensing Boiler

Given:

Boiler capacity at design = 500 MBH

Boiler efficiency at design = 83%

Hot water supply temperature at design = 180 F

For the current hour the boiler load is 370 MBH

The hot water supply temperature for the current hour has been reset to 170 F

Solution:

$PLR = Q_{load} / Q_{cap} = 370 / 500 = 0.74$

$R_{cycle} = 1.0$ since PLR is ≥ 0.10

$HWST_c = 82.2$ C (at design condition of 180 F)

$$
\begin{aligned}
F_{design} = \ & 1.111720116 \\
& + 0.078614078\,(1.0) \\
& - 0.400425756\,(1.0)^2 \\
& - 0.000156783\,(82.2)^2 \\
& + 0.009384599\,(1.0)\,(82.2) \\
& + 0.234257955\,(1.0)^3 \\
& + 0.00000132927\,(82.2)^3 \\
& - 0.004446701\,(1.0)^2\,(82.2) \\
& - 0.0000122498\,(1.0)\,(82.2)^2
\end{aligned}
$$

$F_{design} = 0.9781$

$HWST_c = 76.7$ C (at operating condition of 170 F)

$$
\begin{aligned}
F_{boiler} = \ & 1.111720116 \\
& + 0.078614078\,(0.74) \\
& - 0.400425756\,(0.74)^2 \\
& - 0.000156783\,(71.1)^2 \\
& + 0.009384599\,(0.74)\,(76.7) \\
& + 0.234257955\,(0.74)^3 \\
& + 0.00000132927\,(76.7)^3 \\
& - 0.004446701\,(0.74)^2\,(76.7) \\
& - 0.0000122498\,(0.74)\,(76.7)^2
\end{aligned}
$$

$F_{boiler} = 1.0155$

$\eta_{boiler} = (\eta_{design})\,(F_{boiler}) / (F_{design}) = (0.83)\,(1.0155) / (0.9781) = 0.8617$

$Q_{input} = (Q_{load} / \eta_{boiler}) \times R_{cycle} = (370 / 0.8617) \times 1.0 = 429.4$ MBH

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D. Condensing Boiler: Efficiency = f(PLR, HWST)

With this option HAP uses curve fit performance model which adapts the U.S. Department of Energy EnergyPlus curve fit representing a condensing boiler. This is a 2-dimensional model in which performance is a function of both part-load ratio and hot water supply temperature (HWST).

Efficiency calculations for this modeling option are as follows:

PLR = larger of { Q_{load} / Q_{cap} or 0.10}

where:

PLR	=	Boiler part load ratio, decimal.
Q_{load}	=	Boiler load, MBH
Q_{cap}	=	Boiler design capacity, MBH
0.10	=	The minimum unloading point is assumed to be 10% of design capacity. If the ratio of load to capacity is less than 10%, the boiler will operate at 10% capacity but will cycle on and off during the hour to meet the heating demand.

Cycling ratio is calculated as:

$R_{cycle} = 1.0$　　　　　　　　　　　if PLR > 0.10

$R_{cycle} = (Q_{load} / Q_{cap}) / (0.10)$ if PLR = 0.10

Boiler efficiency is calculated as:

$\eta_{boiler} = (\eta_{design}) (F_{boiler}) / (F_{design})$

where:

η_{boiler}	=	Efficiency of boiler at given PLR and hot water supply temperature operating conditions, decimal.
η_{design}	=	Efficiency of boiler at rated capacity, decimal. This value is specified by the user.
F_{boiler}	=	Boiler efficiency correction factor, decimal. This factor accounts for changes in efficiency between the design condition and the current hour's part-load and off-design HWST conditions. This curve is obtained from EnergyPlus.
	=	1.124970374 + 0.014963852 (PLR) − 0.02599835 $(PLR)^2$ − 0.00000140464 $(HWST_c)^2$ − 0.00153624 (PLR) $(HWST_c)$
F_{design}	=	Boiler efficiency design correction factor, decimal. This factor corrects for the fact the EnergyPlus condensing boiler curve represents a boiler at a specific design hot water supply temperature condition. To apply the curve at other design hot water supply temperatures, the curve must be corrected. F_{design} is calculated using the equation above for F_{boiler} using input values of PLR =1.0 and $HWST_c$ = design supply hot water temperature for the boiler being modeled.
$HWST_c$ =		Hot water supply temperature delivered by the boiler, converted to degrees Celsius. The temperature in deg C is required because that was the basis for the EnergyPlus curve fit.

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Example: Condensing Boiler Model

Given:

Boiler capacity at design = 500 MBH

Boiler efficiency at design = 90%

Hot water supply temperature at design = 140 F

For the current hour the boiler load is 370 MBH

The hot water supply temperature for the current hour has been reset to 130 F

Solution:

$PLR = Q_{load} / Q_{cap} = 370 / 500 = 0.74$

$R_{cycle} = 1.0$ since PLR is ≥ 0.10

$HWST_c = 60$ C (at design condition of 140 F)

$$F_{design} = 1.124970374$$
$$+ 0.014963852 (1.0)$$
$$- 0.02599835 (1.0)^2$$
$$- 0.00000140464 (60.0)^2$$
$$- 0.00153624 (1.0) (60.0)$$
$$F_{design} = 1.0167$$

$HWST_c = 54.4$ C (at operating condition of 130 F)

$$F_{boiler} = 1.124970374$$
$$+ 0.014963852 (0.74)$$
$$- 0.02599835 (0.74)^2$$
$$- 0.00000140464 (54.4)^2$$
$$- 0.00153624 (0.74) (54.4)$$
$$F_{boiler} = 1.0557$$

$\eta_{boiler} = (\eta_{design}) (F_{boiler}) / (F_{design}) = (0.90) (1.0557) / (1.0167) = 0.9345$

$Q_{input} = (Q_{load} / \eta_{boiler}) \times R_{cycle} = (370 / 0.9345) \times 1.0 = 395.9$ MBH

If you have further questions about this subject and you are located in the US or Canada, please contact Carrier software support at **software.systems@carrier.utc.com**. Otherwise, please contact your local Carrier sales office for assistance.

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