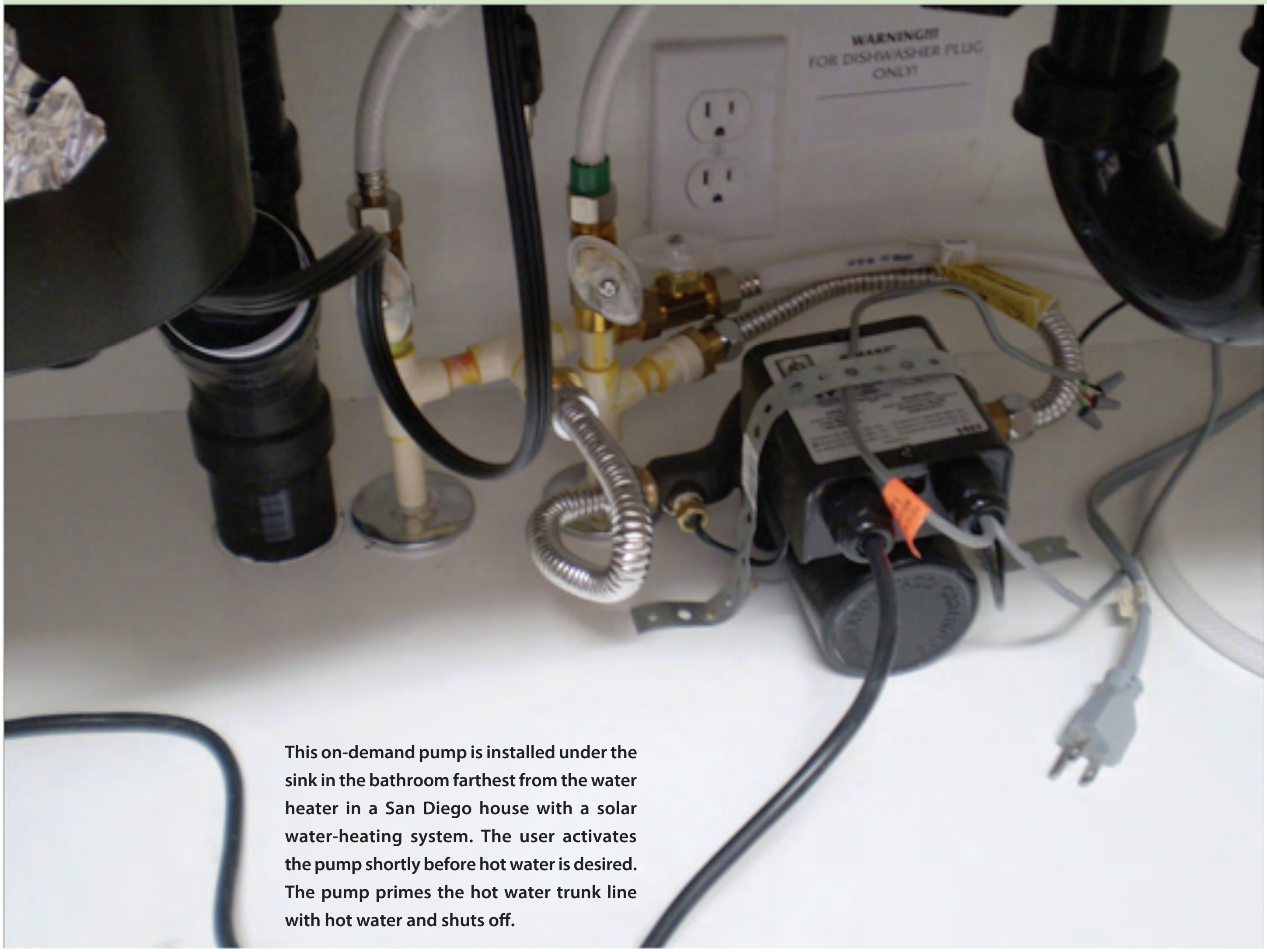

GARY KLEIN

This on-demand pump is installed under the sink in the bathroom farthest from the water heater in a San Diego house with a solar water-heating system. The user activates the pump shortly before hot water is desired. The pump primes the hot water trunk line with hot water and shuts off.

Optimizing for High-Performance Solar Water-Heating Systems

What's the best supplemental heater? We look at the issues and options, concluding this two-part series.

By **GARY KLEIN**

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You've squeezed the water and energy inefficiencies from your hot water distribution system and determined that you can't live without a backup for your solar water-heating system (see part one of this article, September/October issue: solartoday-digital.org/solartoday/20100809). Now it's time to size and select your supplemental heater.

What Size Supplemental Heater Do You Need?

Most solar water-heating systems are, in fact, preheating systems. The solar portion of a solar thermal system heats the water whenever the sun is shining and stores the hot water in a tank so that it can be used whenever the demand arises. We want to avoid overheating the water in the tank and the fluid in the panels as much as possible, and we don't want the panels or exposed piping to freeze.

The size of the supplemental heater depends only partly on the amount and temperature of the stored solar-heated water. The supplemental water heater needs to do three things:

1. Be able to meet the entire load when the sun hasn't shined strongly in several days;
2. Accept or otherwise deal with very hot sun-heated water, say, 180°F (82°C) or hotter;
3. Boost the temperature as little as 1°F at a flow rate as small as 0.25 gallons per minute (gpm) when the water temperature in the solar storage tank is off by just a little bit and the demand for hot water is small.

So, if we expect a "seamless" solar water-heating system, the supplemental water heater must be able to do the entire job expected of the water-heating system regardless of how much energy has been provided by the sun. That effectively means that we have duplicate systems. Hmmm.

The supplemental heater needs to be able to meet the entire load. Customers want "continuousness" from their hot water system, not recovery rate, which implies that they have run out of hot water. According to the people I have interviewed, continuousness means never running out in their getting-ready-for-work shower. This can be accomplished in any of three ways: a large-enough storage tank with hot-enough water; a burner or element large enough to sustain any desired flow rate; or a combination of some stored volume and a more modest burner or element (60,000–120,000 British thermal units, or Btu, per hour, or 15–30 kilowatts). The latter is my preference.

Table 1 shows the capacity of different types of water heaters needed to continuously heat 1 gallon per minute at various temperature differences between incoming cold water and the set-point temperature. When the water is cold — requiring a large temperature rise — such as when it has been cloudy in the winter, the power input needs to be large. Remember to proportion the capacity of the heater up or down depending on the actual flow rate of hot water.

The supplemental heater needs to be able to accept or deal with very hot preheated water. That is not a problem for storage water heaters, as they accept whatever temperature water they are given and turn on only when their thermostats register cold water. Standard gas-fueled tankless water heaters do not like high-temperature inlet water. The manufacturers advise the use of a tempering valve between the solar storage and the cold water to ensure that the water entering the tankless unit is cold enough for the water heater to fire. That reduces the amount of solar-heated water used in any given hot water event, keeping more of the sun's energy stored in the tank for future use. But the point of the solar water-heating system is to use it, isn't it? *Electric* tankless water heaters appear to have no problem with high-temperature preheated water, they don't turn on when the temperature is above the set point, and when it is below the set point, they heat only the amount needed.

The supplemental heater needs to be able to provide very small amounts of additional energy for boosting. This requirement is a challenge for most tankless water heaters, particularly the most commonly advertised gas units, those without any built-in storage. Although it is, as yet, rare to see hot water outlets with such low flow rates in residential applications, it is common in the hot portion of a hands-free faucet found in public lavatories. It is also common when a

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TABLE ONE

Capacity of Water Heater Required to Heat 1 Gallon per Minute

	Electric Power (kW)						Fossil Fuel (Btu)					
	Coefficient of Performance (COP)						Thermal Efficiency					
Temp. Rise (˚F)	Resistance			Heat Pump			Natural Gas, Propane, Oil					
	0.9	0.95	1	2	2.5	3	70%	75%	80%	85%	90%	95%
1	0.16	0.15	0.15	0.07	0.06	0.05	714	666	625	588	555	526
5	0.81	0.77	0.73	0.37	0.29	0.24	3,570	3,332	3,124	2,940	2,777	2,631
10	1.63	1.54	1.46	0.73	0.59	0.49	7,140	6,664	6,248	5,880	5,553	5,261
20	3.26	3.08	2.93	1.46	1.17	0.98	14,280	13,328	12,495	11,760	11,107	10,522
30	4.88	4.63	4.39	2.20	1.76	1.46	21,420	19,992	18,743	17,640	16,660	15,783
40	6.51	6.17	5.86	2.93	2.34	1.95	28,560	26,656	24,990	23,520	22,213	21,044
50	8.14	7.71	7.32	3.66	2.93	2.44	35,700	33,320	31,238	29,400	27,767	26,305
60	9.77	9.25	8.79	4.39	3.52	2.93	42,840	39,984	37,485	35,280	33,320	31,566
70	11.39	10.79	10.25	5.13	4.10	3.42	49,980	46,648	43,733	41,160	38,873	36,827
80	13.02	12.34	11.72	5.86	4.69	3.91	57,120	53,312	49,980	47,040	44,427	42,088
90	14.65	13.88	13.18	6.59	5.27	4.39	64,260	59,976	56,228	52,920	49,980	47,349

TABLE TWO

Percent of Mixed-Temperature Water that is Hot (Mixed Temperature 105˚F)

Cold Water Temperature (˚F)	Hot Water Temperature (˚F)										
	110	**115**	**120**	**125**	**130**	**135**	**140**	**145**	**150**	**155**	**160**
35	93%	88%	82%	78%	74%	70%	67%	64%	61%	58%	56%
40	93%	87%	81%	76%	72%	68%	65%	62%	59%	57%	54%
45	92%	86%	80%	75%	71%	67%	63%	60%	57%	55%	52%
50	92%	85%	79%	73%	69%	65%	61%	58%	55%	52%	50%
55	91%	83%	77%	71%	67%	63%	59%	56%	53%	50%	48%
60	90%	82%	75%	69%	64%	60%	56%	53%	50%	47%	45%
65	89%	80%	73%	67%	62%	57%	53%	50%	47%	44%	42%
70	88%	78%	70%	64%	58%	54%	50%	47%	44%	41%	39%
75	86%	75%	67%	60%	55%	50%	46%	43%	40%	38%	35%
80	83%	71%	63%	56%	50%	45%	42%	38%	36%	33%	31%
85	80%	67%	57%	50%	44%	40%	36%	33%	31%	29%	27%
90	75%	60%	50%	43%	38%	33%	30%	27%	25%	23%	21%
95	67%	50%	40%	33%	29%	25%	22%	20%	18%	17%	15%
100	50%	33%	25%	20%	17%	14%	13%	11%	10%	9%	8%
101	44%	29%	21%	17%	14%	12%	10%	9%	8%	7%	7%
102	38%	23%	17%	13%	11%	9%	8%	7%	6%	6%	5%
103	29%	17%	12%	9%	7%	6%	5%	5%	4%	4%	4%
104	17%	9%	6%	5%	4%	3%	3%	2%	2%	2%	2%
105	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

regular faucet is turned on only a portion of the way. We can predict that, over the next decade or so, the industry will update its standards and policymakers will establish incentives encouraging the use of very low-flow-rate faucets in residential applications.

Here is the problem: It takes roughly 40,000 Btu per hour (10 kilowatts) to keep up with a flow rate of 1 gpm at a 70°F temperature rise. Conversely, if we have a burner that is firing at 40,000 Btu per hour, we must have some combination of flow and temperature rise to absorb the heat; for a given input heat rate, as the temperature rise gets lower, the flow rate must increase.

The better electric tankless units can modulate so as to provide only the incremental heat needed to match the flow rate and temperature rise. That's an advantage these electric tankless water heaters have over most gas tankless units.

So, if we only need 1°F temperature rise and a flow rate of 0.25 gpm, we only need to supply the water with 125 Btu per hour before accounting for the efficiency of the water heater. (Use Table 1 to check this.) That is two orders of magnitude smaller than the smallest burner on current gas tankless water heaters; effectively, the capacity of the burner at the low end of their modulation range is too big. The manufacturer's recommended solution is to increase the flow rate so that the device fires, but that makes it almost impossible to use low-flow-rate outlets.

Even when the solar-preheated water is colder than the desired set-point temperature, a high "cold" input water temperature will give a gas tankless heater problems unless a tempering valve has been installed between the cold inlet and the solar storage. Table 2 shows the percentage of hot water required to provide a mixed temperature of 105°F (41°C). At a more typical flow rate of 1 gpm and a set-point temperature of 120°F (49°C), if the preheated "cold" input water is entering the tankless water heater at 100°F (38°C), we need only 25 percent, or 0.25 gpm, to be heated by the tankless water heater. The tempering valve needs to bring in more cold water to lower the input water temperature until the gas tankless can fire properly.

Two considerations must be addressed to determine which one is the limiting factor: the minimum flow rate required for firing or the minimum firing rate of the burner. Assuming that the minimum flow rate needed to fire the gas tankless heater is 0.75 gpm, the temperature of the tempered mix needs to be no more than 60°F (16°C). Assuming that the minimum firing rate of the burner is 15,000 Btu per hour, it is capable of sustaining approximately a 25°F (14°C) temperature rise at a 1 gpm flow rate (Table 1). However, since the set-point temperature is 120°F (49°C), this would mean that the input water temperature would be 95°F (35°C). Table 2 shows that this means that 40 percent, or 0.4 gpm, would be the hot portion of the mix. This is too low for the unit to start firing. The minimum flow rate is the limiting factor.

Turning on and sustaining operations at these very low flow rates is a challenge for most electric tankless water heaters, too. Some can turn on and sustain operations at 0.25 gpm, with a few going even lower; however most need at least 0.5 gpm to operate. In addition, the better electric tankless units can modulate so as to provide only the incremental heat needed to match the flow rate and temperature rise, starting from very small combinations of flow rate and temperature and ranging up to support the peak hot water-flow rates found in typical households. That's an advantage these electric tankless water heaters have over most gas tankless units.

From an efficiency perspective, it makes no sense to use an atmospheric gas storage water heater as the supplemental heater, because it has a hole up the middle (the flue) that must remain open for when the unit needs to fire. Well-insulated electric tanks are a reasonable solution and have been common practice for many years. Condensing gas storage heaters make for good supplemental heaters. However, I am wary of using any water heater that has the supplemental water heater combined in the tank that stores the solar-heated water. The problem is dueling controls.

Here's a typical scenario: It is 7 a.m., and the household has left for work and school, not to return until after 4 p.m. The temperature of the water in the tank is cold enough that the thermostat wants to call for heat, so it tells the burner or element to turn on. The burner or element heats the tank, which takes from 30 minutes to two hours … just in time for the sun to reach the point of providing significant energy to the panels. The sun then does its job all day long, putting energy into the tank. But instead of starting with cold water in the tank, it starts with hot water. This reduces the efficiency of

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This solar water-heating system, installed on a Florida house, serves six to seven people on average. The storage tank, the controls and the electric tankless heater are shown in the lower photo. Note the subpanel to the right of the heater.

the solar heat transfer and tends to result in very high storage-tank temperatures.

It is, of course, possible to turn off the element or burner so that it does not fire automatically — assuming you remember to reset the controls on cloudy days. But since most customers want seamless solar, if they forget to reset the controls on overcast days, they are unlikely to want to wait for the water to get hot when they come home. I suppose we need an app for that! It is also possible to purchase storage tanks in which the supplemental heater heats only the upper portion of the tank, leaving room for the sun to do its job in the lower portion. That is a better option, but unless the burner or element is large enough or the volume at the top of the tank is large enough to keep up with the hot water needed for at least one shower, our customers may be unhappy on some occasions.

What is the Best Supplemental Heating System?

In my opinion, the best *technical* match for solar preheating is a water heater that will heat the water only when necessary (on-demand) and only as much as needed to reach the set-point temperature. Until 2010, I would have said that the only technology that can do the job properly was a fully modulating electric tankless water heater. This year, a condensing gas tankless water heater (rated EF = 0.95) with 2 gallons of built-in storage (covered under the legal definition of instantaneous water heaters) became available and appears to be capable of doing the job properly and efficiently. The photos at left show a solar water-heating system that uses a modulating electric tankless heater as the supplemental water heater.

I know that there are issues, real and perceived, with the use of tankless water heaters.

Gas tankless units are expensive to retrofit, because we're likely to need to increase the size of the gas line and change the venting. Incoming hard water also may necessitate increased maintenance, something we are unaccustomed to doing with our water heaters. Electric tankless units have their challenges, as well. They require space in the distribution panel, the capacity of the unit may be limited by the amperage rating of the panel (according to the National Electric Code, a 200-amp service can handle a 30-kilowatt unit), and the wiring to the unit needs to be larger in diameter than that used for standard electric water heaters. As with gas tankless heaters, the hardness of the incoming water can lead to increased maintenance.

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Electric tankless heaters also raise concerns at the electric utilities, which worry that these large-capacity heaters will cause problems with the distribution system. Common concerns include dimming lights due to high-amperage draws when units turn on; flicker due to rapid modulation of large-capacity devices; and overheating distribution transformers, particularly if several households served by that transformer have electric tankless units. These are valid concerns, but if the wiring to and in the house and the transformer serving the house are all sized correctly and the electric tankless has a good modulation strategy, they are just that, concerns. (By the way, I have heard similar concerns from gas utilities when multiple gas tankless water heaters are installed at the end of a distribution line.)

Since we plan to have a supplemental water heater, it makes sense to size the solar water-heating system to be more strictly a preheater. In addition, since we implemented all of the efficiency measures discussed in part one of this article and our demand for heat has been reduced by 25 to 50 percent, the panel sizing needs to be reduced proportionately. Further, if our system was only able to heat the water halfway from incoming cold water temperature to the desired hot water temperature, we would still have a 50 percent solar fraction, wouldn't we?

The typical recommendation for the relationship between panel size and storage volume seems to be 2 gallons of storage per square foot (81.5 liters per square meter) of panel. We should look more carefully at increasing this to 3 gallons per square foot (122 liters per square meter) or maybe even 4 gallons per square foot (162 liters per square meter). Perhaps this simpler solar system would be much more affordable, and we would see greater market penetration, too. **ST**