Work-Assisted Heating

How Application of Thermodynamics Principles Can Double the Efficiency of Our Heating Systems

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Introduction

After several decades of relative inattention, serious energy policy debate has regained political prominence in the United States. For the most part, the discussion has been focused on changes to our methods of producing electricity and powering vehicles; that is, solar photovoltaic systems, wind turbines, renewable bio-fuels, and electric vehicles. While these technologies have strong merit and address major energy use within the economy, a very significant sector has largely been excluded from thoughtful examination: *fossil fuel heating*. Here, where the improvement potential is very large and attainable, widespread misconception has masked the opportunity. Specifically, no significant improvement in how we produce heat from combustion has entered into our public discussion because we rate the equipment utilized for heating applications, furnaces and boilers, to be near perfect – 85 to 95% efficient. Using a more sophisticated definition of efficiency, based on the Second Law of Thermodynamics, these appliances are actually far worse than their theoretical maximum. From a thermodynamicist's perspective, the actual efficiency is only about 9%. If heating appliances are redesigned with a methodology that addresses the wide shortcomings revealed by this viewpoint, our effective fuel usage (and carbon footprint) can be reduced several fold.

All Energy Is Not Equal

Heating appliances produce heat by burning fuel followed by dissipation of the residual energy to the media needing to be warmed (i.e. air, water, etc.). Modern appliances are able to accomplish this effectively with nearly all the combustion energy contained in the fuel being transferred. The hot gases, which begin the post-combustion process at approximately 3000 F, are cooled continuously to several hundred degrees as the energy is extracted. In a simplistic sense, the energy extracted in the beginning of the process, in cooling the gas from say 3000 to 2500 F, is equivalent to that removed in its late stages, from 700F to 200F. While both 500 degree segments represent about 1/6 of the process and likewise represent equal amounts of thermal energy, they are, in fact, very different in their worth. The upper segment, being at a very high temperature, has the means to produce a great deal of work via a heat engine. The low-end segment, that which has been cooled, can produce work but only very meager amount[1]. The property, which differentiates the value of the energy contained in a substance relative to its ability to do work, is termed "availability" or "exergy."

The heating process described above, where heating is accomplished by simply transferring the heat from the flue gases to the heated media, results in no net loss of thermal energy; one extremely high temperature fluid is dramatically cooled with the heat energy being imparted into the cold media. However, while we began with one fluid having the ability to produce work and one that could not, the unfortunate outcome is two tepid fluids, neither of which has any

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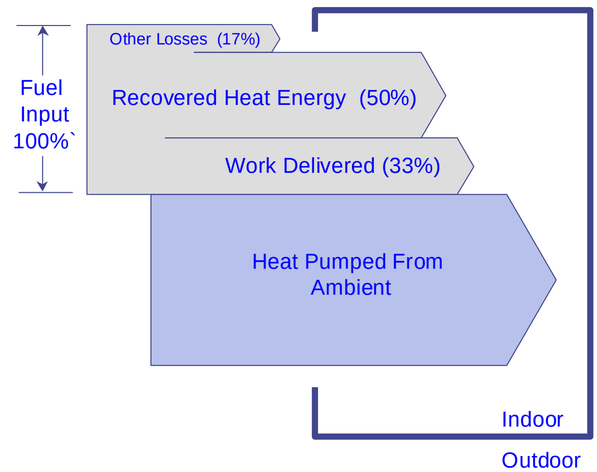
[1]Heat engines, which encompass all fossil-fueled engines, base their output on the temperature difference between combustion gases and their surroundings. Performance (i.e., efficiency and output) rapidly deteriorates if the process gases are cooler. Operating an engine from a low temperature heat source (such as a waste heat steam) is a marginal preposition due to this thermodynamic limitation.

significant ability to produce work. The "exergy" that existed has been almost entirely expended, irreversibly, without the creation of work. Work, as explained below, is far more valuable than simple heat.

Figure 1 – Energy Flow in Heat Pump



Work-Assisted Heating

The value of the energy as work, rather than simple heat, is that work can be used to move substances against an opposing force. A machine incorporating work can be constructed to transport heat from one region to another against an unfavorable temperature gradient. Moreover, the amount of heat that can be moved is many times the heat contained in the fuel powering the machine. As such, an appliance designed for heating, which incorporates work, can effectively increase its output many times. In theory, the multiplying effect is about 10 times. In practice, using existing technology, the effect is a two to three-fold benefit, which is in itself enormously beneficial.

The machine that enables heat energy to be moved from a cold space to a warm space against the temperature gradient is a classic "heat pump". The principle components are a compressor, a heat engine, and heat exchangers. The engine powers the compressor, doing work, through a standard vapor-compressor cycle. The cold side of the cycle extracts heat from the ambient air and the warm side delivers the heat to the warmed media, such as building air or process water. The work to operate the engine extracts the very high quality energy of the fuel – the upper temperature range – and the residual low-quality/low-availability energy is used for additional, direct heating[2]. A typical energy diagram for the process is depicted as Figure 1. As shown, the process extracts most of the fuel's energy in form of shaft work and recovered heat, but there is an additional energy pick-up that is absent in the conventional form of the appliance: *the heat which is pumped or reclaimed from the facility surroundings*. The efficiency has increased in this example from about 83% to about 200%[3]. As noted above, the thermodynamicist would agree with the two-fold efficiency increase, but the relative change would be based on the 9% starting point. Suffice it to say, the process efficiency has more than doubled.

[2] The exhaust gas exits the heat engine depleted of its high temperature energy. Its usefulness for creating work is negligible – its exergy is mostly depleted – but it is entirely usable for direct heating.

[3] The heat pump appliance commonly used for space heating is electrically powered. As such, it loses the benefit of the recovered heat (50%) as this energy is discarded at the power plant. Electric transmission losses further decrease electric heat pump performance.

Potential Domestic Impact on Energy Consumption

Conventional heating appliances – furnaces, water heaters, and boilers – are utilized in all sectors of the economy. In 2007, our domestic use of fossil fuels for space and water heating in the residential and commercial sectors was about 12 Quads[4]. Most of that energy was in the form of natural gas (85%) and the remainder of the heating was accomplished with oil. To put these figures in perspective, the total U. S. import of oil in that year was 28.5 Quads, while our Alaskan oil production was 1.54 Quads. If the "work" cycle methodology described above were applied universally, the savings would be on the order 4-6 Quads, the equivalent of several Alaskan oil fields. The potential benefit of revising our approach to heating is striking. The environmental/ carbon benefit would be proportional to the fuel saved, while the problematic investment required in developing additional oil and gas supplies would be avoided. Our capital investment would find better purpose in the deployment of high efficiency equipment.

Proposed Product Application – Natural Gas Water Heating

Among the choices for introducing a heat pump product, commercial water heating stands out as the most easily exploited application. Our reasons are threefold:

- *Annual usage*. In order for the product to recoup the additional capital investment for the higher efficiency product, heavy usage is beneficial. Space heating furnaces do not meet this requirement, but water heater applications with near 24/7 operation are common – hotels, hospitals, nursing homes, dormitories, etc. For example, a large commercial water heating system could easily use $100,000 in gas annually. Reducing this total with the heat pump to $40,000 would provide annual savings of $60,000 to be applied to increased investment and maintenance. Conversely, if the base application of the heater resulted in a much lower figure, say $10,000 annually, a reduction to $4,000 would yield a $6,000 annual benefit, not nearly as compelling for the same capital expenditure.
- *System Integration*. Commercial water heating systems are usually centrally located within a facility. Supplementing the existing system with the new product is greatly simplified; interconnection can be made at a single point of interconnection with inexpensive and unintrusive piping. In contrast, commercial space heating with warm air furnaces is accomplished with small, dispersed units. Integration would require numerous small heat pumps, a rather difficult system to distribute heat.
- *Common Application*. High-usage water heating systems are common throughout the country, consisting of (but not limited to) hotels, motels, health clubs, schools, dormitories, hospitals, and nursing homes. Space heating and industrial applications would likewise be included. A single, modular product could cover a wide range of the market.

Reconfiguring Tecogen Product for Water Heating

Tecogen currently manufactures and services a successful line of natural gas engine-driven chillers, which are the close cousins of heat pumps (see Figure 2). Sizes range from about 25 refrigeration Tons (35 horsepower) to 400 Tons (300 horsepower) and all contain the critical prerequisite: an efficient heat engine operated on natural gas[5]. The essential difference between

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[4] Based on US department of Energy data (see http://www.eia.doe.gov/) .

[5] The ideal water heating fuel is natural gas. It is universally available, produced domestically and it has the lowest carbon content per unit of energy of any fossil fuel. Tecogen's chillers utilize natural gas fuel engines reconfigured from automotive, gasoline, application. The automotive engine as the product basis is Tecogen's hallmark; these are efficient, durable, simple to service, and remarkably inexpensive. Modifications to run on natural gas with very low emissions is readily accomplished and the supply chain is essentially unlimited.

the air-conditioning product and the heat pump is that the refrigeration cycle is reversed. The water connections to the chiller cool the water, while those connections on the heat pump accomplish the opposite effect (heating) when the cycle is reversed. With rather straightforward engineering, Tecogen's chiller products can be reconfigured as heat pumps. The smaller Tecogen chillers, the RT Series, would suit the commercial water heating market very well. As such, we will examine the potential benefits of a heat pump water heater derived from our RT series.

Figure 2 – Tecogen RT Series Water Chiller (35 Horsepower)

Performance

Figure 3 depicts the anticipated performance of a Tecogen system re-engineered for the heat pump application in a typical 120 F heating application. We have plotted efficiency relative to ambient temperature as outdoor conditions – the pumped heat source – effects the performance of the system (more work is required to "pump" the heat on colder days). In any case, the efficiency improvement is dramatic when compared to the conventional heater. The efficiency on a 40 F day is twice the conventional system and triples at about 80 F.

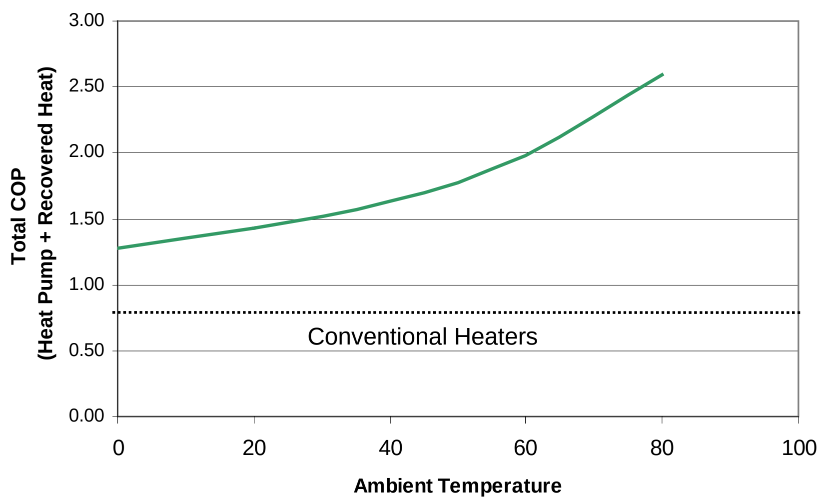

Figure 3 – Estimated Performance of Heat Pump Water Heater at Various Ambient conditions (water heated to 120 F).

Table 1 summarizes the annual benefits of a single heat pump machine, sized to our RT Series product line, operating under heavy usage (6000 hours/year) in various U. S. metropolitan areas. The product water heater output is 500,000 BTU/hour (5 therms) which would require a nominal engine size of 35 horsepower. The conventional water would consume 6 therms of fuel per hour, while the "RT-based" water heater, with the benefit of work, is able to heat the equivalent amount of water at about 40% of the fuel usage.

As shown in the table, fuel savings at today's natural gas prices ($1/Therm) would be about $17-20,000 annually. Higher price scenarios are also given in the table ($1.50 and $2.00 per Therm) with proportionally increased savings. Prices as high as $2.00/Therm were achieved several years ago and we would anticipate the long-term trend to be upward, particularly if the affect of a carbon tax (or carbon trade program) were included.

Relative Greenhouse Gas Benefit

As shown in Table 1, the annual carbon savings for the heat pump water heater is 130 Tons/year. A useful perspective is to compare the carbon benefit of this product to a solar photovoltaic system of equal annual carbon savings. Using generally accepted rules of thumb for West Coast PV installations [6], a 90 kW PV array would be required to match the 130 annual tons of carbon emissions reduction of a heat pump water heater. That PV system would cost about $400,000 and require 9,000 square feet of exposure area, 1/5 of an acre. By contrast, the heat pump installation cost would be on the order of 10% of the PV system and require less than 1% of the space.

Table 1 – Annual Performance and Carbon Benefit for Gas-Fired Heat Pump Water Heater Relative to Conventional System (Based on 83% Efficient Conventional Heater)

		Annual Fuel Savings 6000 Hours/Year Operation			
		Fuel Price/Therm			
Metro Area	**Relative Fuel Consumption**	**$ 1.00**	**$ 1.50**	**$ 2.00**	**Annual Carbon Savings (Tons)**
Atlanta	38%	$ 22,446	$ 33,669	$ 44,892	131
Boston	43%	$ 20,711	$ 31,066	$ 41,422	121
Chicago	43%	$ 20,602	$ 30,904	$ 41,205	121
Cleveland	43%	$ 20,711	$ 31,066	$ 41,422	121
Dallas Ft Worth	36%	$ 23,096	$ 34,645	$ 46,193	135
Denver	42%	$ 20,855	$ 31,283	$ 41,711	122
Houston	35%	$ 23,566	$ 35,349	$ 47,133	138
Los Angeles	38%	$ 22,446	$ 33,669	$ 44,892	131
Miami	31%	$ 24,795	$ 37,193	$ 49,590	145
New York	41%	$ 21,253	$ 31,880	$ 42,506	124
Phoenix	32%	$ 24,651	$ 36,976	$ 49,301	144
Portland	42%	$ 21,072	$ 31,608	$ 42,145	123
San Diego	37%	$ 22,735	$ 34,102	$ 45,470	133
San Francisco	41%	$ 21,470	$ 32,205	$ 42,940	126
Seattle	43%	$ 20,783	$ 31,175	$ 41,566	122
Tampa	33%	$ 24,145	$ 36,217	$ 48,289	141
Averages	**39%**	**$ 22,209**	**$ 33,313**	**$ 44,417**	**130**

[6] Solar system installed cost is equal to $4,500/kW with a useful output of 23% of full rating.