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Teaching the Theory and Realities of 2nd Law Heating Systems

Abstract

In response to concerns about global warming by CO2, and depletion of non renewable fuels and need for jobs, there has been increasing interest in teaching renewable or so called Green Energy technologies. They are typically defined as wind, solar and bio-fuels. However, the most potential exists where the most is wasted. The author asserts this is the non-obvious home furnace or heating systems. One reason the home furnace is overlooked is some furnaces are advertised to have a 96 % efficiency.

It is notable that prior to the last generation, the best residential furnaces were typically 80 % efficient. This meant that 20 % of the heat went up the chimney in the form of elevated temperature combustion products and water vapor. The step improvement to 96 % efficiency was obtained by increasing the heat recovery surface area with a secondary heat exchanger, which cooled the combustion products down close to space temperature and also condensed most of the vapor in the combustion products. The chimney was replaced with a clothes drier type vent to the side of the house. Thus, virtually all of the sensible heat and most of the latent heat in the combustion products was recovered. The result has been called a condensing furnace, which was commercialized in the mid 1980s.

Chimney furnaces need the lower density of the elevated temperature combustion products to cause them to go up the stack by free convection. The cooled combustion products of a condensing furnace are not buoyant and thus require forced purging. This has been achieved in some furnaces by pulse combustion with tuned valves, or alternatively by a conventional combustion chamber and a motor driven fan to draw the products from the furnace.

This near 100 % efficiency suggests there is very little room for improvement. However, thermodynamic students should recognize this is a 1st law efficiency. It is the ratio of space heat delivered to the heat value or the amount of heat produced by burning the fuel. If the 2nd law is considered it is recognized that heat must be transferred over a very large temperature difference between the combustion products and the space temperatures. This results in a large entropy production and wasteful irreversibility. It also means a lost opportunity to convert the high temperature heat mechanical power or electricity, that are highly refined forms of energy much more valuable than low temperature heat.

An understanding of the 2nd law is needed to explain why a 1st law efficiency of over 100 % is possible. The explanation can be challenging. It should start with defining an ideal heating system, which would have no entropy production and thus no irreversibility. This means determining the minimum amount of fuel to produce the required space heat.

An Ideal Heating System Defined

An ideal heating system could be achieved by burning the fuel in an ideal engine and using the mechanical power from the engine to drive an ideal heat pump, and also recovering and delivering all engine rejected heat to the space. The next step is to define the ideal fuel burning engine and the ideal heat pump. The ideal heat pump will be the well established Carnot heat pump, because inside space receives heat at constant temperature and the outside air provides heat at a constant temperature.

The corresponding Coefficient of the Carnot heat pump, defined as the ratio of the delivered heat to the mechanical power input, is COP = Thotspaceair/(Thotspaceair-Tcoldoutsideair). On a day with an outside air temperature of 0 F or 460 R and an inside temperature of 70 F or 530 R the Carnot heat pump will have a COP = 7.57.

The efficiency of an ideal engine is not the Carnot cycle, because the heat source is the combustion products that release heat over the entire temperature range in the cooling off process from Thotmax down to Tcold. The corresponding ideal fuel burning engine is the Wicks cycle[1,2,3] that has an efficiency equation Efficiency= 1- Tcold * ln(Thotmax/Tcold)/ (Thotmax-Tcold).

Assuming a maximum combustion product temperature of 2500 R and a cold or ambient heat sink temperature of 500 R the ideal fuel burning engine will be .5976 or 59.76 % efficient. Thus, the ideal heating system can have a first law efficiency that is the product of this engine efficiency and heat pump Coefficient of Performance. The resulting 1st law efficiency for these conditions is 4.52 or 452 %. The 2nd law efficiency is the ratio of actual to ideal 1st law efficiencies. Thus, this ideal system will have has a 2nd law efficiency of 100 %.

Fuels and Possibilities for Realistic 2nd Law Heating Systems

The next step is to identify and analyze a practical 2nd Law heating system. It is noted that a variety of fuels are possible for both an engine and a condensing furnace. However, the environmentally best fuel is natural gas, and the second choice would be propane. Carbon rich fuels such as natural gas, which is mostly methane, have the largest difference between low and high heat values. The Marks Mechanical Engineering Handbook gives a low heat value of 21,518 (Btu/lb) and a high heat value of 23,890 (Btu/lb) which is larger by 11%. This difference can also be estimated. Methane has a formula of CH_4, which means every pound yields 2.25 lbs of water vapor. Since the heat of vaporization for water is about 1000 (Btu/lb), the additional heat that can be released by condensing the water vapor is 2,250 (Btu/lb). This is the approximate difference between the published high and low heating values.

There is no single method to make a 2nd law heating system. One possibility is to scale up an old time ammonia and water absorption cycle refrigerator, that is typically fueled by natural gas or propane. While operating as a refrigerator these systems had a Coefficient of Performance of about 30 % defined as the ratio of low temperature heat absorbed in the evaporator to the heat released by burning the fuel. Placing the evaporator outside the house and the combustion chamber and condenser in the house can yield a 1st law efficiency of 130 %, because the heat from the fuel and evaporator are both transferred to the inside of the house.

A more practical method to obtain a 1st law efficiency higher than 100 % is by burning the fuel in an internal combustion engine with the mechanical power produced driving a compression cycle heat pump, and then also recovering most of the engine waste heat to further heat the inside space. A gasoline type spark ignition engine can be converted to natural gas or propane. The engine can convert 25 % of the fuel to mechanical power. A heat pump COP of 3 will result in 75 % of the fuel energy to be delivered as space via the heat pump condenser. Most of 75 % of the fuel that is rejected by the engine can be recovered from cylinder cooling and the exhaust. The result is a heating system approaching a 1st law efficiency of about 150 %.

Electricity Producing Condensing Furnace as an Alternative 2nd Law System

Another concept that achieves comparable energy efficiency benefits while requiring fewer components is the Electricity Producing Condensing Furnace.[4&5] It was patented in 1987 by Frank Wicks. The motivation was to improve upon the then recently commercialized condensing furnace. It was recommended for support by the National Institute for Standards and Technology, and built and demonstrated with funding from the Department of Energy. It received an ASME Outstanding Energy Innovation Award in 1988.

The inventor claimed a 1st law efficiency of about 160 %. This is based upon converting 20 % of the fuel energy to electricity which is assumed to be four times more valuable than space heat and then recovering the remainder as low temperature space heat.

It is notable that electricity is always more valuable than low temperature heat. Electricity can easily be degraded to heat via electric resistance. However, electricity is a highly refined form of energy that requires relatively expensive and sophisticated apparatus for production such as heat engines, hydro dams and turbines, wind turbines or photovoltaic devices, and plus the additional equipment for transmission and distribution.

The following example supports the assertion that electricity is typically four times more valuable than heat. A resident may pay 7.50 ($/Million Btu) for natural gas and .10 ($/kwhr) for electricity, which converts to 30 ($/Million Btu) for electricity. These values will vary with time and location, but the factor of four may be an underestimate.

This analysis required recognizing not all forms of energy are of equal value. Electricity is a highly refined form of energy. Alternatively, the factor of four can be claimed because the electric power system delivers only about 25 % of the heat value of the fuel to the customer. The other 75 % is lost via discharge heat to the rivers or cooling towers at the power plant and through transmission and other conversions.

Alternatively, the Electricity Producing Condensing Furnace can be explained as a small factory that processes the input of $100 of the raw material into output products comprised of $80 of heat and $80 of electricity. Since $100 produces $160, a monetary efficiency of 160 % can be claimed.

The Electricity Producing Condensing Furnace is comprised of a module containing a single cylinder gasoline engine, converted to natural gas, with a direct shaft drive to a single phase capacitor start induction motor, which inherently becomes a generator after starting the engine. The engine exhaust goes through a primary and then condensing heat exchanger then exits via a water drain and plastic duct.

The shaft mounted engine cooling fan also serves to circulate the space air that enters at about 70 F. It is drawn through a condensing heat exchanger, then across the engine and generator and then through the primary heat exchanger, and discharged to the hot air duct at about 140 F.

The horizontal shaft engine is rated at 10 hp at 3600 rpm, but operates at about half speed for higher efficiency, longer life and less noise and vibration. The generator is rated at 6 hp as a single phase motor at 1740 rpm. The speed increases to about 1860 rpm when it becomes a generator. Input natural gas flows at about 50 cubic foot per hour corresponding to 50,000 (Btu/hr). An engine efficiency of 25 % and generator efficiency of 80 % produces 10,000 (Btu/hr), which is about 3,000 watts, of grid connected electricity. The remaining 40,000 (Btu/hr) is recovered as space heat.

The Electricity Producing Condensing Furnace was designed to be a compatible replacement for a gas hot air condensing furnace. It uses the same fuel, cold and hot space air ducts, and thermostat for ON/OFF control. However, a standard 230 volt clothes dryer type circuit is recommended, rather than the 115 volt hook up for a typical furnace.

An ON signal energizes two electromagnets. One closes a switch between the motor and grid. The other opens the fuel valve to the engine. The grid turns the motor that cranks the engine which starts producing power in about one second. The motor inherently becomes a generator producing 3000 watts. Any excess power can flow back to the electric grid, which observed as a backwards running meter.

The Electricity Producing Condensing Furnace has a subtle simplicity because of multiple uses of components, and its interface with the grid. The module serves as both a furnace and electric generator. The fan cools the engine and generator, and also circulates the space air. The starting motor is also generator. The engine also serves the furnace functions of combustion chamber and ignition and provides some of the heat transfer surface. The exhaust stroke provides the forced purging of combustion products.

The result is that no heat and no electricity wasted. All heat is used within the building. The grid transmits the extra power to other users, or provides the extra power needed in the residence. The grid also provides virtual electric storage at no capital cost and no conversion losses. It provides the starting power, along with speed and voltage control once the electric motor becomes a generator.

There is a recognized risk. If the operating engine fails due to loss of fuel or other reasons, the generator will revert back to a motor and will continue to crank the engine. The safeguard that has been designed into the controller is a reverse power relay that must be bypassed by a time delay relay to get started. A manual reset button and relay prevents an automatic restart after an abnormal condition trip.

It should be noted that prior to 1950 most residential heating was done by coal or wood. Failure to pay attention to temperature and to regularly load fuel could mean a cold living space. It was the introduction of oil and gas fueled furnaces that required electric motors and fuel flow controls that also allowed for thermostats for automatic temperature control.

The home heating system has become a matter of out of sight and out of mind for most residents. More recent capability can allow remote monitoring of furnaces by service companies that can perform routine maintenance, and also rapidly respond to abnormal conditions.

A Long Slog

History shows that it can take decades between time of concept and commercialization. The steamboat, bicycle, automobile, air conditioning, gas and oil furnaces, and the condensing furnace are some examples. The concept was necessary, but far from sufficient. Problems had to be identified and resolved by many years of research, development and testing of prototypes.

It has also been a challenge to explain to non-engineers and engineers and students why a condensing furnace was better than a chimney furnace. It has been an even bigger challenge to explain how an Electricity Producing Condensing Furnace represents an even larger efficiency fuel efficiency improvement.

The first prototypes demonstrated the principle. Remaining challenges included showing the acceptability of an internal combustion engine operating inside a residence and related issues of engine life, maintenance, noise, vibration, equipment protection, safety, codes, standards and certification.

Engineering students at Union College made important progress by designing and testing improved prototypes. Meanwhile, Honda Power Equipment had the resources to resolve all of the challenges. In 2006 Honda introduced a functionally equivalent system called Mini Combined Heat and Power (CHP) or Freewatt. More than 50,000 are operating in Japan. These systems have been installed throughout Europe and the United States by ECR International of Utica, New York. In 2011 it has been recognized by the Environmental Protection Agency with an Emerging Technology Award.

Multiple Benefits

Renewable, alternative energy and "Green Technologies" are being promoted for the multiple benefits of fuel conservation, decrease of greenhouse gases and new business and job opportunities. Solar, wind, geothermal and tides that use no fuel are relatively easy for the public to understand. However, new systems that use fuel more effectively can have more benefits.

The Electricity Producing Condensing Furnace has the potential of replacing every gas or propane furnace in the world. In the future it should be recognized as the efficiency standard for all furnaces. It can claim to produce fuel free electricity if it replaces a chimney furnace. If it replaces a condensing furnace it will have a marginal efficiency of 100 % for the electricity that is generated. The corresponding greenhouse footprint will be .4 lbs of CO_2 per kwhr, which is a 75 % reduction relative to a coal burning central generating plant.

Coal has been the dominant fuel for producing electric power. Though highly polluting, there were no effective environmental restrictions and it was abundant and relatively cheap. More recently required pollution controls have further increased the cost. There is no practical way to prevent the release of CO_2 to the atmosphere.

Meanwhile, natural gas is becoming more available, but with environmental concerns related to increased extraction from deep shale. Resource poor countries will continue to import expensive liquefied natural gas. European countries are largely dependent on Russian gas that is transported by pipeline. The long term availability of gas, but at increasing costs, provides additional incentive for more efficient end use, whether by central power plants using combined gas and steam cycles, or potentially by the Electricity Producing Condensing Furnace.

The future of nuclear power is another consideration. It has been producing an important portion of the electricity during the last generation, but this fraction is has decreasing because of retirements and difficulty in building more nuclear plants. Additional capacity is being lost because of the major earthquake damage in Japan in 2011 and resulting mandates to close down operating nuclear plants in Germany, and possibly the United States.

The Electricity Producing Condensing Furnace can have other near and long term economic benefits. It can create a new industry and manufacturing jobs. The engine will probably require more maintenance, which can also provide more employment. The lower combined heat and electricity bill should provide the user with a net savings, and extra money to spend elsewhere.

Once established, it should define a new efficiency standard for every gas and propane furnace throughout the world.

Education and Why Not Hydrogen Fuel Cells?

Educating the general public, professional engineers and scientists and engineering students can intersect, particularly on matters related to energy and the environment. An example is the idea of a sustainable future with hydrogen after the oil runs out. This vision has been described by Jeremy Rifkin. He is a writer and an environmental activist. He wrote a popular book that has sold more than a million copies. It is entitled "The Hydrogen Economy: The Creation of the World Wide Energy Web and the Distribution of Power on Earth" [6] which is described as the next great economic revolution.

Accordingly, the author is often asked, including by reviewers, why not hydrogen fuel cells that can also produce electricity and heat, rather than the "Electricity Producing Condensing Furnace." It is a good question. Fuel cell research is being performed in universities and industrial laboratories around the world. Auto manufacturers continue to research and promote fuel cells for future vehicles.

The author answers these queries by first explaining that although hydrogen is called a fuel, it really is not a fuel, in the same way that electricity is not a fuel. Hydrogen and electricity are highly refined mediums for transferring energy. Neither one is found in a useful form in nature. Electricity must be produced by a conversion from mechanical energy via engine powered magnets, or alternatively by a chemical reaction in batteries or in a fuel cell.

Water should be recognized as hydrogen that has already been burned. Extraction of hydrogen from water requires a reverse oxidation. It requires electricity, or more complicated chemical processes. Alternatively, hydrogen can be extracted from hydrocarbon fuels, the best being methane or natural gas, because of the higher hydrogen content.

Accordingly, the author believes the most realistic 2nd law system fuel conservation and reduced CO_2 production is by providing electricity as a co-product of space heating, and will continue to be for the next generations.

The recently developed methods for enhanced production of natural gas from shale via hydraulic fracturing should extended the years of natural gas heating, and thus the longer term viability and benefits from the Electricity Producing Condensing Furnace. It readily interfaces with the existing natural gas and electric power infrastructure. It uses the natural gas that is already being used for heating only, and readily interfaces with the electric power system, with mutual benefits.

No specific student surveys have been performed related to the engineering education benefits of the Electricity Producing Condensing Furnace. It has been a platform for senior projects and summer research, via building and testing several prototypes, and co-authoring papers (reference 4). It has also been introduced into a Heating, Ventilation and Air Conditioning course and a senior level Thermal and Fluid Systems design course. Along with wind, solar, coal, wood and oil, it was evaluated as an alternative to the existing central heating system that is done via natural gas boilers and steam pipes.

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