



Thermodynamics of Cogeneration

An Online Continuing Education Course for Engineers

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Introduction

Since deregulation of the electric power industry, cogeneration (satisfying electrical and thermal energy needs from the same generating source) has become popular. Cogeneration plant projects can be developed by merchant power companies or by industrial hosts on a decentralized basis. In either case, the thermal efficiencies claimed by developers and/or by combustion turbine manufacturers are often exaggerated or inflated to values beyond those permitted by the laws of thermodynamics. It is incumbent on engineers and others in the energy industry to be critical of such claims and to be able to counter those that may otherwise cause the industry to lose credibility.

Since the discovery of fire by early man, he has been converting the chemical energy stored in certain substances (fuels) to thermal energy to warm himself and to cook his food. Much later he discovered how to harness the energy in wind and water and convert that to mechanical work to grind flour and to power looms. When he finally discovered how to release the chemical energy of fuels and put it to use in the form of mechanical work, the industrial age began, and the science of thermodynamics was born. Since that time, we have been striving to obtain and transport the maximum amount of useful energy with the minimum expenditure of chemical, and more recently, nuclear energy. Even though wind, water, and solar energy conversion systems contribute, we still depend on combustion as the primary source of the power and that sustains our way of life for the foreseeable future. As the availability of fuels and the undesirable results of combustion have increased, the quest for more efficient and effective means of producing useful thermal, electrical, and mechanical energy has become more of a concern.

As these concerns have migrated from the concerns of the engineer to the concerns of the accountant, the politician, the merchant power developers, and the policy makers, the definitions of certain terms and the very laws of thermodynamics have become warped. This was noted in an editorial in a recent issue of Power Magazine. This editorial cites cases where the distinction between the terms "lower heating value (LHV)" and "higher heating value (HHV)", and "reliability" and "availability" have been blurred by those advocating certain energy policies, and where the second law of thermodynamics has been ignored in some cases when quoting thermal cycle efficiencies. It has become essential that engineers in the energy field re-

acquaint themselves with some basic definitions and principles, recognize fallacies when encountered, and be able to confidently counter them.

This course will concentrate on the laws of thermodynamics, and at the risk of seeming too basic for Professional Mechanical Engineers, will review some old ground in order to be more understandable for EEs, CEs, and others.

The First Law

The first law of thermodynamics is straightforward and is easily understood. It is based on the Conservation of Energy, which states that energy can be neither created or destroyed, but can be transformed from one form to another. Placing certain limitations on the Conservation of Energy principle, the first law may be stated as: The total amount of all types of energy within any isolated system will remain constant unless energy is entering or leaving the system through its boundaries, and the net increase or decrease of the energy within the system will be exactly equal to the net amount of energy which has passed through the boundaries. A simple example is the gradual temperature rise of a shaft bearing from the stopped to the steady running condition (mechanical energy, or work, being converted to thermal energy, or heat). The conversion of energy in this case is undesirable, but unavoidable, and is usually circumvented in thermodynamic studies using the fictional "frictionless bearing". The conversion factor between thermal and mechanical energy commonly used in English units is 778 ft-lb per Btu, and is assigned the symbol "J". (for Joule's equivalent).

The first law of thermodynamics, therefore, may also be expressed as: **Thermal energy and mechanical energy are mutually convertible in the ratio of 778 ft-lb per Btu.**

It must be noted that the first law makes no distinction between forms of energy, or between energy and work, and does not mention the restrictions on transforming energy from one form to another. This is why the first law analysis alone is not sufficient in comparing power cycles where different forms of energy are involved, such as in cogeneration processes. Cogeneration cycles generally convert the chemical energy in fuels to electric energy, and utilize the otherwise "waste heat" in an application of thermal energy, such as district heating or an industrial process. There is no doubt that cogeneration as such does conserve energy, reduce environmental impact, and save money. But this useful technology can be harmed by irresponsible marketing hype and exaggerated claims of efficiency.

Cogeneration

A typical cogeneration plant burns natural gas in a combustion turbine and exhausts the high temperature combustion products through a heat recovery steam generator (HRSG), which produces process or heating steam. Cogeneration plant efficiencies are commonly reported by a first law analysis, which adds the net electrical output to the useful thermal energy output and divides the sum by the energy (heating value) of the fuel consumed. By this method, efficiencies as high as 85% can be reported. This analysis fails, however, to account for the relative value of the two different energy stream outputs. Electrical energy is of a very high value. It can do many types of work, can be easily transmitted long distances, and can be nearly completely converted to thermal or mechanical energy. Thermal energy, on the other hand, is much less versatile. It cannot be easily transported, and its conversion to work is much less than 100%. The relative value of the two energy streams should be compared through a second law analysis in order to realistically evaluate a cogeneration application.

The Second Law

The second law of thermodynamics states the restrictions on converting energy from one form to another. The second law cannot be stated as simply as the first law, and perhaps be best understood through its implications. One of these implications is that it is possible to totally convert work into heat, but only to partially convert heat into work.

The portion of the heat that can be converted into work depends on the temperature level of the heat. That is, the ratio of the absolute temperatures between the heat source and the surroundings (heat sink). Given a source of heat coupled with a heat/work cycle, only a portion of this heat can be converted to work. The rest must be rejected as heat to the stored energy of a sink. Also, heat, in the absence of some form of external assistance, can only flow from a hotter to a colder body.

Entropy

As much as I would like to, we cannot discuss the second law without defining entropy. Entropy is a property of a substance at a given state point, as are pressure, specific volume, and temperature. As such, it can be quantified for any state point of the working substance. Entropy is symbolized by the letter "s", and has the units Btu per lb per degree F. For a reversible process:

$q = \int T ds$ Btu/lb, where q is the heat transferred and T absolute temperature, or
 $ds = dq/T$, or
 $\Delta s = \int dq/T$

Entropy may be thought of as a degree of disorder. In nature as in any irreversible (real) thermodynamic process, it is always increasing. All this means that according to the second law, you can't get sumptin' for nothin'. In fact, you always get less efficiency and more entropy!

Reversibility

Entropy can also be thought of as a measure of irreversibility. A process is reversible if the working substances can be returned to their original states along the same process line without any energy input. Reversible processes are "ideal", and can only be approached in the real world. Reversible processes have no change (increase) of entropy. They are said to be isentropic. Any irreversibility increases entropy. Any transfer of heat, for instance, is irreversible because heat can only flow from hot to cold.

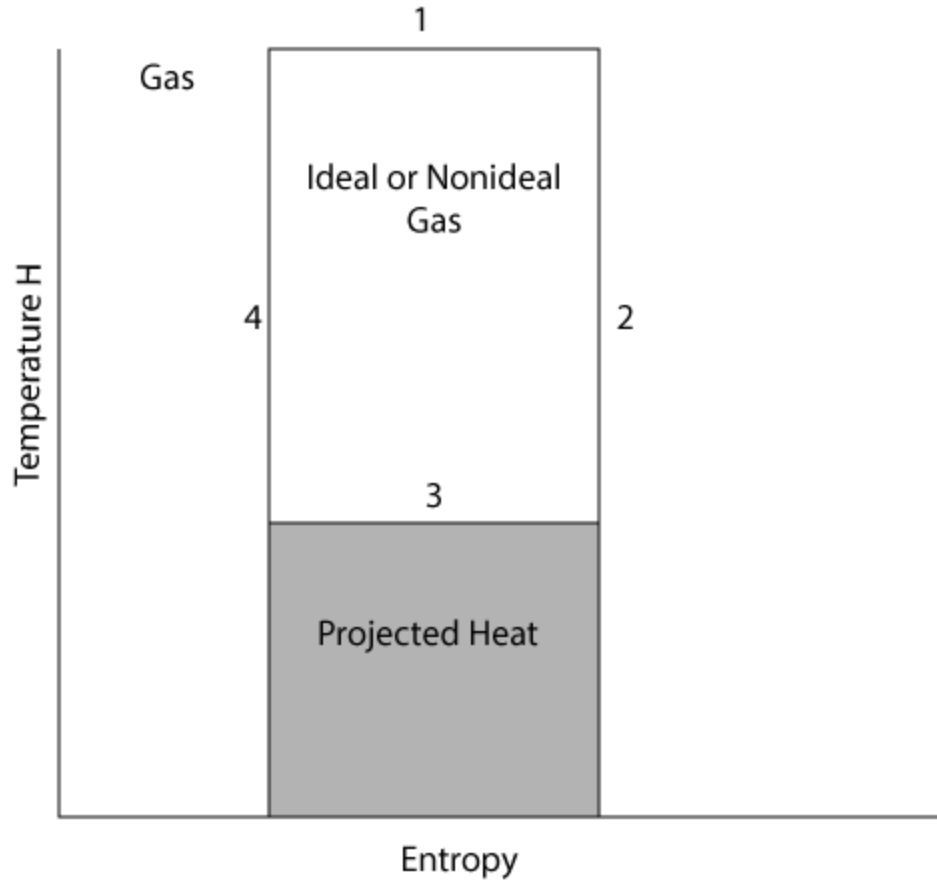
Cycle Diagrams

When processes connect back to the starting point, a cycle is defined. It is convenient to analyze heat engines and thermodynamic cycles by diagrams with absolute temperature as the vertical axis and entropy as the horizontal axis. Heat quantities are then represented by the area under a heat transfer process line. ($dq = \int T ds$). These are referred to as T-s diagrams.

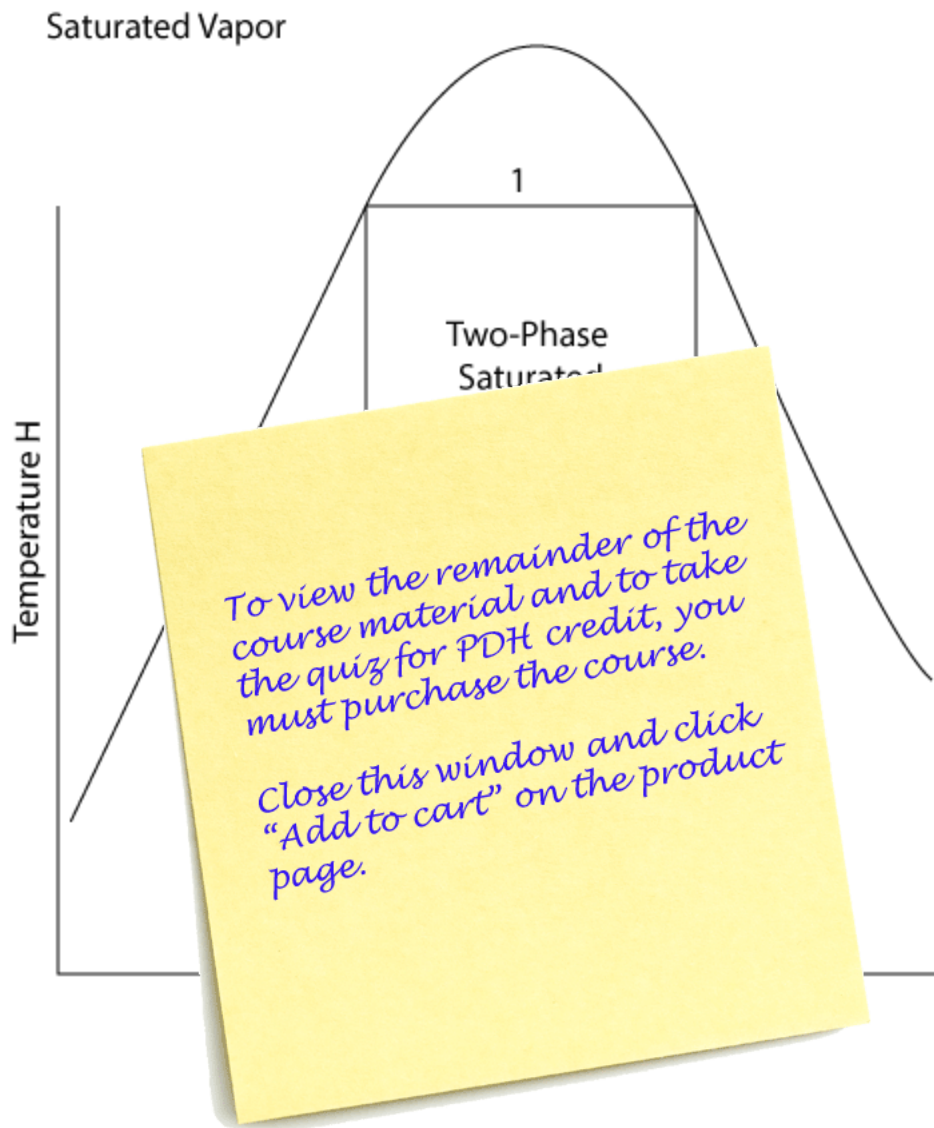
Carnot Cycle

A cycle that illustrates the basic second law principles is the Carnot cycle. Although it is an "ideal", or fictitious cycle, the Carnot cycle is widely used as a basis for heat engine performance.

5a. Temperature - Entropy Diagram.



5b. Temperature - Entropy Diagram.



As represented on a temperature-entropy diagram, the Carnot cycle is a rectangle consisting of a constant temperature heat addition process from an appropriate heat source (1), an isentropic expansion process (2), a constant temperature heat rejection to a heat sink (3), and adiabatic isentropic compression back to the starting point (4). The heat is added at a constant temperature T_1 and the heat is rejected at a constant temperature T_s .

From the definition of entropy ($dq = \int T ds$), the heat added during process #1 is equivalent to the area under the heat added process line, q_1 . Likewise, the heat rejected during process #3 is not available for conversion to work, and is equivalent to the area under the process line q_3 , the