

---

## **AC 2011-2088: ON THE WORK BY ELECTRICITY IN THE FIRST AND SECOND LAWS OF THERMODYNAMICS**

### **Hyun W. Kim, Youngstown State University**

Hyun W. Kim, Ph.D., P.E. Hyun W. Kim is a professor of mechanical engineering and the coordinator of the mechanical engineering graduate program at Youngstown State University. He has been teaching and developing courses in the fluid thermal area and conducting research in advanced thermodynamics, advanced fluid mechanics, and computational fluid mechanics and heat transfer . He is a Professional Mechanical Engineer in Ohio and is currently conducting applied research in fluid power control and computational fluid dynamics with local industries. Dr. Kim received a B.S.E. degree from Seoul National University, a M.S.E. from the University of Michigan, and a Ph.D. from the Univ. of Toledo.

### **Yogendra M. Panta, Youngstown State University**

Dr. Yogendra Panta graduated from University of Nevada, Las Vegas with Ph.D. in Mechanical Engineering in 2008. He is an active member of several engineering societies including ASEE, ASME and APS. Since then, he is actively involved in research areas of Fluid Dynamics, Thermodynamics, and Microfluidics Lab on Chip applications . He has published a book, several articles and presented at several conferences. Dr. Panta has recently developed a new course on "Computational Fluid Dynamics" in the College of STEM at YSU. His research group works on CFD modeling and simulation, microfluidics lab on chip and biofluid dynamics. He is currently serving as an Assistant Professor of Mechanical Engineering at Youngstown State University.

# **On the work by electricity in the first and second laws of thermodynamics**

## **Abstract**

In the first law of thermodynamics analysis, energy transfer by electrical heating elements placed in a system or control volume has been traditionally classified as the electrical work. This classification has been an accepted norm since it neither violates the physical principles nor creates any problems in defining other forms of non-mechanical work in the first-law analysis. However, this practice seems to present a significant problem pertaining to the reversible work and the irreversibility in the second-law analysis.

In this paper, a number of exercise problems containing electrical heating elements have been examined. They were solved by the traditional way for the second-law analysis which produced some questionable results regarding the reversible work and the irreversibility. The apparent discrepancies in the relationship of actual work, reversible work, and the irreversibility might be caused by a combination of the entropy generation during the energy addition process, the initial properties of the system and the surroundings. Based on this study, a change seems warranted for the first and second laws analysis relating to the electrical work.

## **Background**

A typical thermodynamic problem is solved by the traditional methodology of analysis that combines the first and second laws of thermodynamics. The first law describes the principle of conservation of energy and is defined as the net energy transfer into the system being equal to the change of the total energy in the system. Although there may be minor differences in describing the principle by different authors, the first law of thermodynamics is usually given in a general equation form as

$$Q - W = \Delta E \quad \text{or} \quad Q_{\text{in}} - Q_{\text{out}} + W_{\text{in}} - W_{\text{out}} = \Delta E \quad \text{for closed systems}$$

where  $Q$  is the heat transferred to the system,  $W$  is the work done by the system, and  $\Delta E = \Delta U + \Delta(\text{KE}) + \Delta(\text{PE})$

Heat transfer and work are considered as similar forms of energy transfer and thus are not distinctly different to the first law of thermodynamics. The work  $W$  includes the boundary work, shaft work, work done on a surface film, and other forms of non-mechanical work such as work on a simple magnetic substance and work by electricity. The work done by electrical force was originated from Gibbs' idea, according to Hatsopoulos and Keenan<sup>1</sup> who formulated the general definition of work transfer interactions. They stated that "work is an interaction between two systems such that what happens in each system at the interaction boundary could be repeated

while the sole effect external to each system was the change in level of a weight". Fellingner and Cook<sup>2</sup> stated that electrical current crossing a boundary constitutes a work interaction if the sole effect external system could be raising of a weight. Apparently, the raising of a weight translates to the work by the standard definition. Therefore, energy transfer by electrical heating elements placed in a system or control volume has been classified as the electrical work transfer rather than heat transfer from the surroundings. Almost all thermodynamics textbooks<sup>3-7</sup> written in the last few decades define the energy transfer by the electrical heating element as electrical work and contain such problems for exercise. This classification might have been accepted by many authors without much scrutiny since there is no problem in dealing with this form of energy transfer as a non-mechanical type of work in the first-law analysis. In fact, it is more convenient to define the energy transfer as work than heat transfer in the first law analysis. For the energy transfer by the electrical work, there is no need of defining the temperature and the physical boundary of the heating element since only the electrical current crosses the boundary of the system that transfers the work. The heating element is regarded as if it does not exist. It becomes neither a part of the system nor the surroundings. An additional convenience for the electrical work is that, if no other heat transfer is involved, the system boundary can be declared to be adiabatic since the energy transfer is considered only as a work transfer. However, it is not clear whether the original definition of the electrical work made by the earlier-day pioneers can be applied to a system with electrical heating elements, as will be seen in the subsequent analysis.

The second law of thermodynamics brings out the distinction between work and heat transfer in the form of entropy. In the second-law analysis, the Kelvin-Planck and Clausius statements of the second law of thermodynamics are often replaced by an entropy balance equation which quantifies the net entropy into the system plus the entropy generation being equal to the entropy change in the system. This equation is called the second law of thermodynamics for a process. It is written as

$$\text{The second law (Entropy balance): } S_{\text{in}} - S_{\text{out}} + S_{\text{gen}} = \Delta S$$

$$\text{where } S_{\text{in}} - S_{\text{out}} = \sum Q_k/T_k \text{ for closed systems}$$

Heat transfer generally accompanies the entropy change while no entropy is transferred during a process that is involved with work only. The second law of thermodynamics governs the process that can be a reversible, irreversible or impossible. Therefore, energy transfer or energy conversion in these processes must also satisfy the second law of thermodynamics and the relationship between useful work, reversible work, and exergy destruction (or irreversibility<sup>2</sup> or lost available work<sup>3</sup> used by other authors).  $W_u$  is the useful work and is defined as the work that can be utilized for any useful purpose. The reversible work  $W_{\text{rev}}$  is defined as the maximum amount of useful work that can be produced for work producing systems or the minimum work needed for work consuming systems. The exergy  $X$  is a property of the system-environment combination and was often called the availability<sup>4</sup>. The exergy represents the useful work potential of the system at the specified state. The exergy can be transported across the system

boundary by heat, work and mass flow. The exergy balance equation for closed systems is written as:

$$\text{Exergy balance: } X_{\text{in}} - X_{\text{out}} - X_{\text{destroyed}} = \Delta X$$

$$\text{where } X_{\text{in}} - X_{\text{out}} = \sum (1 - T_o/T_k) Q_k + W_u$$

The relationship among the useful work, entropy generation, irreversibility and reversible work is written as:

$$\text{Irreversibility: } I = X_{\text{destroyed}} = T_o S_{\text{gen}}$$

$$\text{Reversible work: } W_{\text{rev,in}} = W_{\text{u,in}} - X_{\text{destroyed}} \text{ for work-consuming systems}$$

$$W_{\text{rev,out}} = W_{\text{u,out}} + X_{\text{destroyed}} \text{ for work-producing systems}$$

Second-law efficiency is defined as the ratio of the actual thermal efficiency to the maximum possible thermal efficiency under the same conditions. For work-consuming systems the second-law efficiency can be written as:

$$\eta_{\text{II}} = W_{\text{rev, in}} / W_{\text{u,in}}$$

It was recently noticed by the authors of this paper that the traditional second-law analysis does not satisfy the above relationship between the reversible and useful work and the irreversibility for some problems of closed systems with electrical heating elements. In the following case studies, these discrepancies are examined and alternative analysis is presented.

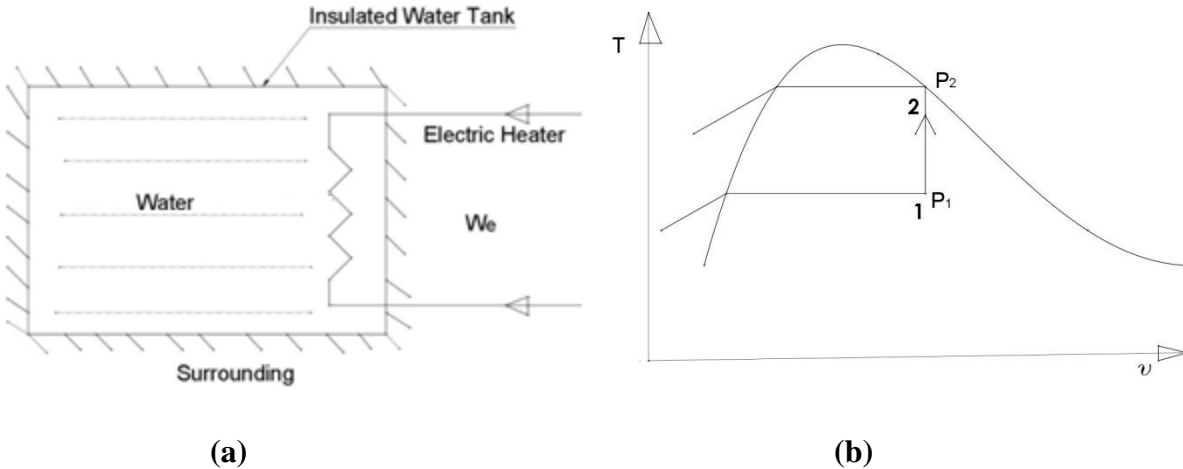
### **Problem statement and traditional analysis**

The undertaking of this study was motivated from an observation of inconsistencies on the second-law analysis of certain problems. The problem originally considered in this paper is from a thermodynamics textbook<sup>3</sup> that has been widely adopted in academia. It is Problem 8-35E, a typical closed system that can be routinely found in any undergraduate textbooks. The original problem reads as follows:

#### ***Original Problem and Analysis***

*A well-insulated rigid tank contains 6 lbm of saturated liquid-vapor mixture of water at 35 psia. Initially, three-quarters of the mass is in the liquid phase. An electric resistance heater placed in the tank is turned on and kept on until all the liquid in the tank is vaporized. Assuming the surroundings to be at 75°F and 14.7 psia, determine (a) the exergy destruction and (b) the second-law efficiency for the process.*

*A simple schematic for the problem is shown in Figure 1, along with a (T-v) diagram illustrating the thermodynamic process.*



**Figure 1** (a) Problem Schematics (b) T-v Diagram

*Under the assumptions of negligible kinetic and potential energy changes, the first-law and second-law analysis yields the following results:*

$$1^{st} \text{ law: } W_{e,in} = W_{u,in} = U_2 - U_1 = m(u_2 - u_1) = 6 \text{ lbm}(1110.9 - 443.7) \text{ Btu/lbm} = 4005 \text{ Btu}$$

$$2^{nd} \text{ law: } S_{in} - S_{out} + S_{gen} = m(s_2 - s_1)$$

$$S_{in} - S_{out} = 0, \text{ and thus, } S_{gen} = 6 \text{ lbm}(1.5692 - 0.70751) \text{ Btu/lbmR} = 461 \text{ Btu/R}$$

$$\text{Irreversibility: } X_{destroyed} = T_o S_{gen} = 2766 \text{ Btu}$$

$$\text{Reversible Work: } W_{rev,in} = W_{u,in} - X_{destroyed} = 1239 \text{ Btu}$$

$$\text{Second-law efficiency: } \eta_{II} = W_{rev,in} / W_{u,in} = 0.309$$

Note that Cengel's notation for work to the system was followed.  $W_{e,in}$  would be equal to  $-W_e$  if the first law were written as  $Q - W = U_2 - U_1$ .

The above analysis follows the currently accepted standard method of thermodynamic analysis. As seen in the above analysis, the exergy destruction is less than the useful work, which yields a positive reversible work and 30.9% of the second-law efficiency. These results appear good and don't seem to present any apparent contradictions as the methodology have been taught the same way for many years. However, a closer look into the analysis reveals some uncertainties that have not been completely addressed. The uncertainties may include following questions. What caused positive entropy generation during the process? With no apparent irreversibility existing or defined in the process, the entropy change in the system must have been caused by energy transfer due to the electrical work. However, work has no effect on entropy transfer. Then, is the process automatically assumed as irreversible? Is the electrical work always associated with the

irreversible process? According to the definition of useful work, the electrical work is equal to useful work. Why is the electrical work equal to a hundred percent useful work while there is no actual work produced or consumed by the system? In addition, what would happen to the analysis if the system contains media other than water or at different initial conditions? A new problem of case study is considered by minimally modifying the original problem. The rigid tank is supposed to contain a saturated mixture of refrigerant R-134a, instead of water, with the same initial conditions. The same method of analysis is applied to this problem, which is called as Case study 1, is shown as follows:

### **Case study 1**

*A well-insulated rigid tank contains 6 lbm of saturated liquid-vapor mixture of refrigerant, R-134a at 35 psia. Initially, three-quarters of the mass is in the liquid phase. An electric resistance heater placed in the tank is turned on and kept on until all the liquid in the tank is vaporized. Assuming the surroundings to be at 75°F and 14.7 psia, determine (a) the exergy destruction (b) the minimum work with which this process could be accomplished, and (c) the second-law efficiency for the process.*

*Known Data) R-134a in an insulated rigid tank,  $Q = 0$ ,  $m = 6$  lbm,  $x_1 = 0.25$ ,  $p_1 = 35$  psia,  $x_2 = 1.0$ ,  $T_o = 75^\circ\text{F}$ ,  $p_o = 14.7$  psia*

*Find) (a)  $X_{destroyed}$  (b)  $W_{rev,in}$  (c)  $\eta_{II}$*

*Assumptions)  $\Delta(ke) = 0$ ,  $\Delta(pe) = 0$*

*Properties) From Table A-12E<sup>1</sup>, saturated water @  $p_1 = 35$  psia,*

$$T_1 = 22.57^\circ\text{F}$$

$$v_1 = v_f + x_1 v_{fg} = 0.01221 + 0.25(1.3369 - 0.01221) = 0.3434 \text{ ft}^3/\text{lbm}$$

$$u_1 = u_f + x_1 u_{fg} = 19.025 + 0.25(78.485) = 38.826 \text{ Btu/lbm}$$

$$s_1 = s_f + x_1 s_{fg} = 0.04267 + 0.25(0.18053) = 0.087803 \text{ Btu/lbmR}$$

*since  $v_1 = v_2 = 0.3434 \text{ ft}^3/\text{lbm}$  and  $x_2 = 1.0$*

$$p_2 = 137.9 \text{ psia and } T_2 = 99.49^\circ\text{F} \text{ by a linear interpolation}$$

$$u_2 = 106.95 + 0.790809(107.51 - 106.95) = 107.39 \text{ Btu/lbm}$$

$$s_2 = 0.2191 + 0.790809(0.21879 - 0.21901) = 0.21884 \text{ Btu/lbmR}$$

*Analysis) 1<sup>st</sup> law:  $W_{e,in} = W_{u,in} = m(u_2 - u_1) = 6 \text{ lbm}(107.39 - 38.826) \text{ Btu/lbm} = 411.38 \text{ Btu}$*

*2<sup>nd</sup> law:  $S_{in} - S_{out} + S_{gen} = m(s_2 - s_1)$*

$$S_{in} - S_{out} = 0$$

$$\text{thus, } S_{gen} = m(s_2 - s_1) = 6 \text{ lbm}(0.21884 - 0.087803) \text{ Btu/lbmR} = 0.7862 \text{ Btu/R}$$

$$\text{Irreversibility: } X_{destroyed} = T_o S_{gen} = (535\text{R})(0.7862 \text{ Btu/R}) = 420.63 \text{ Btu}$$

$$\text{Reversible work: } W_{rev,in} = W_{u,in} - X_{destroyed} = -9.25 \text{ Btu}$$

$$\text{Second-law efficiency: } \eta_{II} = W_{rev,in} / W_{u,in} = -0.0225$$

As seen in the above analysis,  $X_{destroyed}$  (420.63 Btu) is greater than  $W_{u,in}$  (411.38 Btu). Consequently, it yields a negative reversible work of -9.25 Btu and negative efficiency. This is obviously questionable since the larger amount of work potential was destroyed than the useful work in? What caused the amount of exergy destruction larger than the total energy input by the electricity for this seemingly simple closed system with a rigid boundary? To further examine this strange phenomenon, more cases have been studied. Case study 2 is on the refrigerant R-12 and Case study 3 is on the saturated water as in the original problem but at different initial conditions.

### Case Study 2

*A well-insulated rigid tank contains 6 lbm of saturated liquid-vapor mixture of refrigerant, R-12 at -10°F. Initially, three-quarters of the mass is in the liquid phase. An electric resistance heater placed in the tank is turned on and kept on until all the liquid in the tank is vaporized. Assuming the surroundings to be at 75°F and 14.7 psia, determine (a) the exergy destruction, (b) the minimum work with which this process could be accomplished, and (c) the second-law efficiency for the process.*

*Known Data) R-12 in an insulated rigid tank,  $Q = 0$ ,  $m = 6 \text{ lbm}$ ,  $x_1 = 0.25$ ,  $T_1 = -10^\circ\text{F}$ ,  $x_2 = 1.0$ ,  $T_o = 75^\circ\text{F}$ ,  $p_o = 14.7 \text{ psia}$*

*Find) (a)  $X_{destroyed}$  (b)  $W_{rev,in}$  (c)  $\eta_{II}$*

*Assumptions)  $\Delta(ke) = 0$ ,  $\Delta(pe) = 0$*

*Properties) From Table A-11E of the 2nd edition of the same text<sup>3</sup>,*

$$\text{@ } T_1 = -10^\circ\text{F}, p_1 = 19.189 \text{ psia},$$

$$v_1 = v_f + x_1 v_{fg} = 0.01091 + 0.25(1.9727 - 0.01091) = 0.50136 \text{ ft}^3/\text{lbm}$$

$$u_1 = u_f + x_1 u_{fg} = 6.33 + 0.25(69.19 - 6.33) = 22.05 \text{ Btu/lbm}$$

$$s_1 = s_f + x_1 s_{fg} = 0.0146 + 0.25(0.1699 - 0.0146) = 0.053425 \text{ Btu/lbmR}$$

$$\text{since } v_1 = v_2 = 0.50136 \text{ ft}^3/\text{lbm} \text{ and } x_2 = 1.0$$

$p_2 = 81.29 \text{ psia}$  and  $T_2 = 67.11^\circ\text{F}$  by a linear interpolation

$$u_2 = 75.92 + 0.7122(76.85 - 75.92) = 76.58 \text{ Btu/lbm}$$

$$s_2 = 0.1648 + 0.7122(0.1643 - 0.1648) = 0.16444 \text{ Btu/lbmR}$$

Analysis) 1<sup>st</sup> law:  $W_{e,in} = W_{u,in} = m(u_2 - u_1) = 6 \text{ lbm}(76.58 - 22.05) \text{ Btu/lbm} = 327.2 \text{ Btu}$

2<sup>nd</sup> law:  $S_{gen} = m(s_2 - s_1) = 6 \text{ lbm}(0.1644 - 0.053425) \text{ Btu/lbmR} = 0.6661 \text{ Btu/R}$

Irreversibility:  $X_{destroyed} = T_o S_{gen} = (535\text{R})(0.6661 \text{ Btu/R}) = 356.4 \text{ Btu}$

Reversible work:  $W_{rev,in} = W_{u,in} - X_{destroyed} = -29.2 \text{ Btu}$

Second-law efficiency:  $\eta_{II} = W_{rev,in} / W_{u,in} = -0.089$

### Case Study 3

An insulated rigid tank contains 10 kg of saturated liquid water at a constant pressure of 1 kPa. Initially, the quality of the saturated water is 0.9. An electric resistance heater placed in the tank is turned on and kept on until all the liquid in the tank is vaporized. Assuming the surroundings to be at 25°F and 1 atm, determine (a) the exergy destroyed, (b) the minimum work with which this process could be accomplished, and (c) the second-law efficiency during this process.

Known Data) saturated water in an insulated rigid tank,  $Q = 0$ ,  $m = 10 \text{ kg}$ ,  $x_1 = 0.9$ ,  $p_1 = 1 \text{ kPa}$ ,  $x_2 = 1.0$ ,  $T_o = 25^\circ\text{C}$ ,  $p_o = 1 \text{ atm}$

Find) (a)  $X_{destroyed}$  (b)  $W_{rev,in}$  (c)  $\eta_{II}$

Assumptions)  $\Delta(ke) = 0$ ,  $\Delta(pe) = 0$

Properties) From Table A-4 of the text<sup>3</sup>,

$$@ p_1 = 1 \text{ kPa}, T_1 = 6.97^\circ\text{C},$$

$$v_1 = v_f + x_1 v_{fg} = 0.001 + 0.9(129.19 - 0.001) = 116.27 \text{ m}^3/\text{kg}$$

$$u_1 = u_f + x_1 u_{fg} = 29.302 + 0.9(692355.2) = 2148.98 \text{ kJ/kg}$$

$$s_1 = s_f + x_1 s_{fg} = 0.1059 + 0.29(8.869) = 8.088 \text{ kJ/kgK}$$

since  $v_1 = v_2 = 116.27 \text{ m}^3/\text{kg}$  and  $x_2 = 1.0$

$p_2 = 1.157 \text{ kPa}$  and  $T_2 = 8.866^\circ\text{C}$  by a linear interpolation

$$u_2 = 2384.5 + 0.31337(2392.8 - 2384.5) = 2387.1 \text{ kJ/kg}$$

$$s_2 = 8.9749 + 0.31337(8.8270 - 8.9749) = 8.9286 \text{ kJ/kgK}$$



Analysis) 1<sup>st</sup> law:  $W_{e,in} = W_{u,in} = m(u_2 - u_1) = 10 \text{ kg}(2387.1 - 2148.98) \text{ kJ/kg} = 2381.2 \text{ kJ}$

2<sup>nd</sup> law:  $S_{gen} = m(s_2 - s_1) = 10 \text{ kg}(8.9286 - 8.088) \text{ kJ/kgK} = 8.406 \text{ kJ/K}$

Irreversibility:  $X_{destroyed} = T_o S_{gen} = (298.13 \text{ K})(8.406 \text{ kJ/K}) = 2506.1 \text{ kJ}$

Reversible work:  $W_{rev,in} = W_{u,in} - X_{destroyed} = 2381.2 \text{ kJ} - 2506.1 \text{ kJ} = -124.9 \text{ kJ}$

Second-law efficiency:  $\eta_{II} = W_{rev, in} / W_{u,in} = -0.05245$

These two additional cases again show the amounts of the exergy destruction being larger than the work input. These three case studies imply that the problem with the second law analysis was not caused by the media of the systems but the entropy generation, the surrounding temperature, and the initial properties of the system, especially initial temperatures. Before any conclusion is drawn based on the above three case studies, more studies are conducted on water and R-134a with parametric changes.

### Further studies

In order to see the effects of the initial temperature or pressure on the outcome of the analysis, more case studies have been made on saturated R-134a with the exactly same conditions as in the original problem but with different initial pressures of 65 psia, 50 psia, 20 psia, and 5 psia. The results are tabulated in Table 1. As seen in the table, the exergy destruction increases at a rate faster than that of the useful work as the initial pressure or temperature decreases and becomes greater than the useful work at low initial pressures or temperatures.

**Table 1.** Saturated R-134a ( $x_1=0.25$ ,  $x_2=1.0$ ) in a rigid adiabatic tank with different initial pressures  $p_1$ , and  $T_o = 75^\circ\text{F}$

$p_1$ (psia)	65	50	35	20	5
$T_1$ (°F)	54.2	40.23	22.57	-2.43	-53.09
$v_1$ (ft <sup>3</sup> /lbm)	0.19302	0.24637	0.3434	0.57817	2.10297
$u_1$ (Btu/lbm)	47.483	43.634	38.8263	32.126	18.902
$s_1$ (Btu/lbmR)	0.10256	0.096065	0.087803	0.075955	0.0514325
$p_2$ (psia)	233.65	187.9	137.9	82.76	22.01
$T_2$ (°F)	137.16	120.73	99.49	67.83	1.42
$u_2$ (Btu/lbm)	111.16	109.67	107.39	103.59	94.8255
$s_2$ (Btu/lbmR)	0.2168	0.21778	0.21884	0.2203	0.225249
$W_{e,in}$ (Btu)	382.08	396.2	411.38	428.78	455.54
$X_{dest}$ (Btu)	366.71	390.7	420.63	463.35	557.95
$W_{rev}$ (Btu)	15.37	5.5	-9.25	-34.57	-102.41

Table 2 shows similar results from the case studies made on saturated water with the exactly same conditions as in the original problem but with different initial pressures of 20 psia, 0.43016

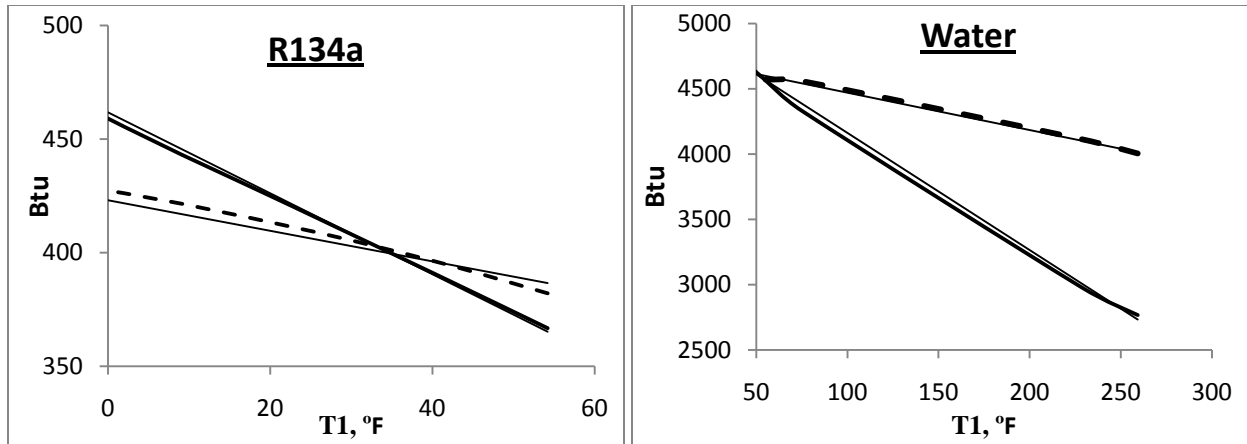
psia, 0.21413 psia, and 0.12173 psia. Again, the exergy destruction increases at a similarly faster rate as the initial pressure or temperature decreases and eventually becomes greater than the useful work at the lowest pressure considered.

**Table 2.** Saturated water ( $x_1=0.25$ ,  $x_2=1.0$ ) in a rigid adiabatic tank with different initial pressure  $p_1$ , and  $T_o = 75^\circ\text{F}$

$p_1$ (psia)	35	20	0.43016	0.21413	0.12173
$T_1$ (°F)	259.25	227.92	75	55	40
$v_1$ (ft <sup>3</sup> /lbm)	2.988	5.0359	184.82	357.6	610.91
$u_1$ (Btu/lbm)	443.47	417.62	291.08	280.22	261.93
$s_1$ (Btu/lbmR)	0.70751	0.68484	0.57533	0.5618	0.55188
$p_2$ (psia)	151.5	87.45	1.9049	0.9312	0.5288
$T_2$ (°F)	359.19	318.21	123.95	99.28	81.2
$u_2$ (Btu/lbm)	1110.9	1103.6	1050.8	1042.97	1037.08
$s_2$ (Btu/lbmR)	1.5692	1.61405	1.92423	1.9837	2.0319
$W_{e,in}$ (Btu)	4005	4115.9	4558.3	4570.5	4650.9
$X_{dest}$ (Btu)	2766	2982.8	4329.9	4564.4	4750.8
$W_{rev}$ (Btu)	1239	1133.1	228.4	6.1	-99.9

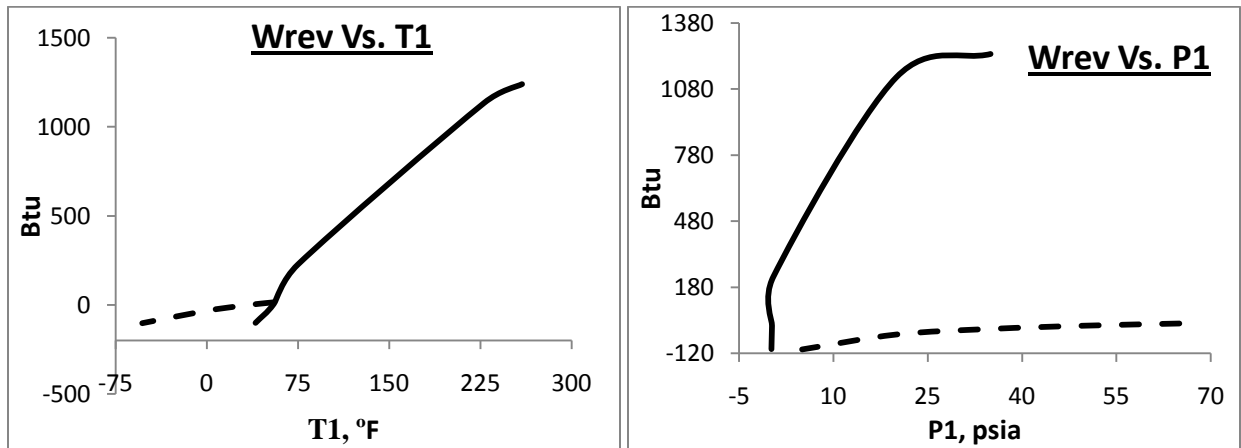
### Interpretation

Why did these surprising results happen to the refrigerants at relatively high initial pressures and the water at very low initial pressure? Based on the case studies and observation on their results, it confirms the suspicion that the problem is linked to the initial conditions rather than the media of the systems when the energy transfer is classified as work. A cursory look on the simple arithmetic indicates that the large exergy destruction was caused by either inaccurate large entropy generation or the surrounding temperature  $T_o$  higher than average temperature of the system. Since the entropy generation or the entropy change during the process remains constant between the fixed initial and final conditions, it may be reasonable to assume that the larger amount of exergy destruction was resulted due to the surrounding or ambient temperature higher than the average system temperature. Despite the fact that the ambient temperature is not at all related to this particular type of energy transfer by work, an arbitrary positive change of the ambient temperature will increase the amount of exergy destruction even more with neither direct causes from the energy transfer nor consequential effects on the entropy change as clearly illustrated in Figure 2. In Figure 2, thick solid and dashed lines indicate the useful work and the exergy destroyed, respectively while thin solid lines are the best fit curves highlighting the slopes of the plot. This arbitrary increase in the exergy destruction definitely causes negative reversible work for some cases with an electrical work and a low initial temperature as illustrated in Figure 3. Solid and dashed lines indicate water and R-134a, respectively in Figure 3.



**Figure 2** (a)  $X_{des}$  vs.  $T_1$  and  $W_e$  vs.  $T_1$  for R 134a (b)  $X_{des}$  vs.  $T_1$  and  $W_e$  vs.  $T_1$  for Water

These additional parametric case studies confirm that the erroneous results are inherently linked to the electrical work and the surrounding temperature. Therefore, the errors might be rectified simply by reclassification of the type of energy transfer.



**Figure 3** (a)  $W_{rev}$  vs.  $T_1$  for Water and R134a (b)  $W_{rev}$  vs.  $P_1$  for Water and R134a

### New method of analysis

The new analysis assumes that the energy transfer from the electrical heating element to the system (R-134a) as heat transfer rather than electrical work. As mentioned earlier in the background section, this energy transfer is actually heat transfer that eventually delivers thermal energy to the system. Unnecessary existence of the entropy generation can be avoided by reclassifying the energy transfer as a reversible isothermal heat transfer, without modifying the essence of the original problem statement as shown below in Case study 4. Some additional statements in describing adiabatic surfaces and deleting the temperature of the surroundings seem minor inconveniences that would avoid major contradiction regarding thermodynamic laws. The problem statement is slightly modified to accommodate new assumptions.

**Case study: New analysis**

A rigid tank contains 6 lbm of saturated liquid-vapor mixture of R-134a at 35 psia. The boundary surface of the tank is well-insulated so that there is no heat gain or loss through the surface. Initially, three-quarters of the mass is in the liquid phase. An electric resistance heater placed in the tank is turned on and kept on until all the liquid in the tank is vaporized. Assuming an isothermal heat transfer, determine (a) the exergy destruction and (b) the reversible work for the process.

Known Data) R-134a in a rigid tank,  $m = 6 \text{ lbm}$ ,  $x_1 = 0.25$ ,  $p_1 = 35 \text{ psia}$ ,  $x_2 = 1.0$

Find) (a)  $X_{\text{destruction}}$  (b)  $W_{\text{rev}}$

Assumptions) a) The heating element represents the surrounding.

b) The electrical current passing through the heating element is controlled such that the temperature of the element is kept identical to that of the system. In other words, the system temperature is equal to the surrounding temperature,  $T = T_o$ .

c)  $W_e = 0$

d)  $\Delta(ke) = 0$ ,  $\Delta(pe) = 0$

Analysis)

The process is reversible since isothermal heat transfer is isentropic.

Thus,  $S_{\text{gen}} = 0$

1<sup>st</sup> law:  $Q = m(u_2 - u_1) = 6 \text{ lbm}(107.39 - 38.826) \text{ Btu/lbm} = 411.38 \text{ Btu}$

2nd law:  $Q / T_{\text{ave}} = m(s_2 - s_1) = 6 \text{ lbm}(0.21884 - 0.087803) \text{ Btu/lbmR} = 0.7862 \text{ Btu/R}$

Thus,  $T_{\text{ave}} = Q / 0.7862 \text{ Btu/R} = 523.24 \text{ R}$

Irreversibility:  $X_{\text{destroyed}} = T_o S_{\text{gen}} = 0$

Reversible work:  $W_{\text{rev}} = W_u + X_{\text{destroyed}} = 0$

Exergy balance:  $X_{\text{in}} - X_{\text{out}} - X_{\text{destroyed}} = X_2 - X_1$

Where  $X_{\text{out}} = 0$  and  $X_{\text{destroyed}} = 0$

$X_{\text{in}} = (1 - T_o / T_o)Q = 0$

$X_2 - X_1 = m(\Phi_2 - \Phi_1)$

$= m[(u_2 - u_1) - T_o (s_2 - s_1) + p_o(v_2 - v_1) + \Delta(ke) + \Delta(pe)] = 0$

## Conclusion

The case studies show that the long held classification of electrical work presents problematic consequences in the second-law analysis. The change from the electrical work to an isothermal heat transfer as shown in the new analysis produces much more consistent results and also provides more reasonable interpretation on useful and reversible work and exergy destruction. For a rigid tank that houses an electrical heating element, it may be completely acceptable to declare zero useful work and zero reversible work and consequently zero exergy destruction since no entropy is generated in the process with an isothermal heat transfer. Therefore, the second law of thermodynamics in this analysis yields the average temperature for the system, which is close to the arithmetic mean temperature of the process. The analysis also confirms that exergy balance for the process is automatically satisfied as shown above.

If the heat transfer between the heating element and the system were assumed as non-isothermal, the heating element would be regarded as a thermal energy reservoir. The process would be irreversible and, of course, there would be positive entropy generation and part of the exergy transfer would be destroyed. The temperature of the heating element, under the assumption, would be higher than the system temperature and not necessarily identical to the surrounding or ambient temperature. The amounts of the entropy generation and the exergy destruction will depend on the assumed value of the temperature of the heating element and the surrounding temperature. The analysis will show that the amount of the reversible work is equal to the amount of the exergy destruction as similarly anticipated in the traditional second law analysis<sup>8</sup>. Other resulting outcomes of the new analysis, which is to be reported in the near future, will not present any problems to the existing thermodynamics principles.

Although further research on this matter may be needed, this study suggests that there should be necessary corrections made in many thermodynamic textbooks regarding the erroneous classification of the electrical work in the first-law analysis and careful re-examination on useful and reversible work, surrounding temperature, and exergy destruction for systems that contain electrical heating elements.

## Bibliography

1. Principles of General Thermodynamics, G. N. Hatsopoulos and J. H. Keenan, 1965, Wiley
2. Introduction to Engineering Thermodynamics, R. C. Fellingner and W. J. Cook, 1985, W. C. Brown Publishers
3. Thermodynamics, An Engineering Approach, 6<sup>th</sup> Edition, Y. A. Cengel and M. A. Boles, 2008, McGraw Hill

4. Fundamentals of Classical Thermodynamics, 2<sup>nd</sup> Ed., G. J. Van Wylen and R. E. Sontag, 1976, Wiley
5. Thermodynamics, W. Z. Black and J. G. Hartley, 1985, Harper and Row
6. Thermodynamics, E. E. Anderson, 1994, PWS Publishing Company
7. Engineering Thermodynamics, 4<sup>th</sup> Ed., M. D. Burghardt and J. A. Harbach, 1993, Harper Collins
8. Advanced Engineering Thermodynamics, 3<sup>rd</sup> Ed., A. Bejan, 2006, Wiley