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Determination of the real power loss for a steam turbine

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All real processes generate entropy and the power/exergy loss is usually determined by means of the Gouy-Stodola law. If the system only exchanges heat at the environmental temperature, the Gouy-Stodola law gives the correct power loss. However, most industrial processes exchange heat at higher or lower temperatures than the actual environmental temperature. To calculate the real power loss it is not correct to use the actual environmental temperature in the Gouy-Stodola law. The first aim of this paper is to show through simple steam turbine example cases that the previous statement is true. The second aim of the paper is to define the effective temperature to calculate the real power loss of the system from the Gouy-Stodola law and apply it to turbine examples. Turbine examples reveal that the sum of the power loss and real power production does not give the correct maximum power production if the real environmental temperature is used in all cases in the Gouy-Stodola law. Example calculations also show that the correct power loss can be defined if the effective temperature is used instead of the real environmental temperature.

Keywords: Gouy-Stodola law, Entropy generation rate, Exergy, Effective temperature

1 Introduction

Exergy is usually defined as the maximum work output attainable in the natural environment, or a minimum work input necessary to realize the reverse process (*Szargut, 2005)*. All real processes generate entropy and loss of exergy is determined by means of the Gouy-Stodola law

$$E_{loss} = T_o\delta \qquad (1)$$

where T_o is the environmental temperature and δ the entropy generation rate. Equation (1) also expresses the improvement potential of the system.

If the system only exchanges heat at the environmental temperature, Equation (1) gives the exact improvement potential of the system. However, most industrial processes exchange heat at higher or lower temperatures than the actual environmental temperature. It is easy to show that in these cases, Equation (1) does not give the real improvement potential of the system, if the actual environmental temperature is used.

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The first aim of this paper is to show through simple steam turbine example cases that the previous statement is true. The second aim of the paper is to define the temperature T_o in Equation (1) to calculate the real power loss of the system. From now on the loss term in Eq. (1) is always called power loss (P_{loss}) to distinguish it from exergy loss (E_{loss}) which is usually calculated using the actual environmental temperature.

One of the simplest processes where the entropy generation occurs is a steam or gas expansion in a turbine. Calculation of the power loss in a turbine using the Gouy-Stodola law has been presented by *Aljundi (2009), Bejan (1996), Kotas (1995), Struchtruo and Rosen (2002), Szargut (2005), Szargut et.al. (1988), Wang et.al. (2008)*. With the exception of Bejan, all authors have used the actual environmental temperature to calculate the power loss. *Bejan (1996)* states that the temperature in Equation (1) falls somewhere between $T_{out,rev}$ and $T_{out,real}$ when the power loss is calculated in a steam expansion. However, Bejan does not give any answer what the exact temperature in Equation (1) should then be. *Lampinen and Wiksten (2006)* have presented in depth analysis of the determination of the correct environmental temperature in Equation (1).

In this paper, we will apply Lampinen's and Wiksten's ideas to calculate the real power loss from Equation (1) to the following example systems; i) steam expansion in a turbine, ii) steam expansion in a condensing turbine + condenser.

2 Calculation of the power loss for a steam turbine

The general method of the calculation of the power loss has been presented in the following papers *(Holmberg, et.al, 2008)* ,*(Lampinen et.al, 2006)* and is not presented in this paper. This chapter only summarises the central results form Holmberg's and Lampinen's papers and shows how to calculate the power loss to systems studied in this paper (see Fig. 1). According to this method, the correlation between the maximum power production, real power production and the the Gouy-Stodola law is defined as follows:

$$P_{max} - P = T_{eff}\delta \tag{2}$$

where P_{max} is the maximum power production, P the real power production, T_{eff} the effective temperature and δ the entropy generation rate. In Eq. (2), T_{eff} is used in the the Gouy-Stodola law instead of the real environmental temperature T_o. The effective temperature in Equation (2) is defined as follows:

$$T_{eff} = \frac{\left(T_2 - T_{2R}\right)}{ln\frac{T_2}{T_{2R}}} \tag{3}$$

where T_{2R} is the theoretical outlet temperature after a reversible process and T_2 the real outlet temperature. If the process is stationary and can be treated as adiabatic the entropy generation rate becomes:

$$\delta = \sum_{i=1}^{n} \dot{m}_i s_{i,out} - \sum_{j=1}^{m} \dot{m}_j s_{j,in} \tag{4}$$

where $\dot{m}$ is the mass flow and s the specific entropy of the flow. Figure 1 shows three systems for which the calculation of the power loss will be illustrated in this paper. Figure 1 also shows how to define the entropy generation rate and the effective temperature for each system. All systems are treated as adiabatic which means that the entropy generation rate can be calculated using Equation (4). If the steam is a mixture of a saturated vapor and water after the expansion, T_2 and T_{2R} are the same and $T_{eff} = T_2$ *(Lampinen, Heikkinen, 1996)*.

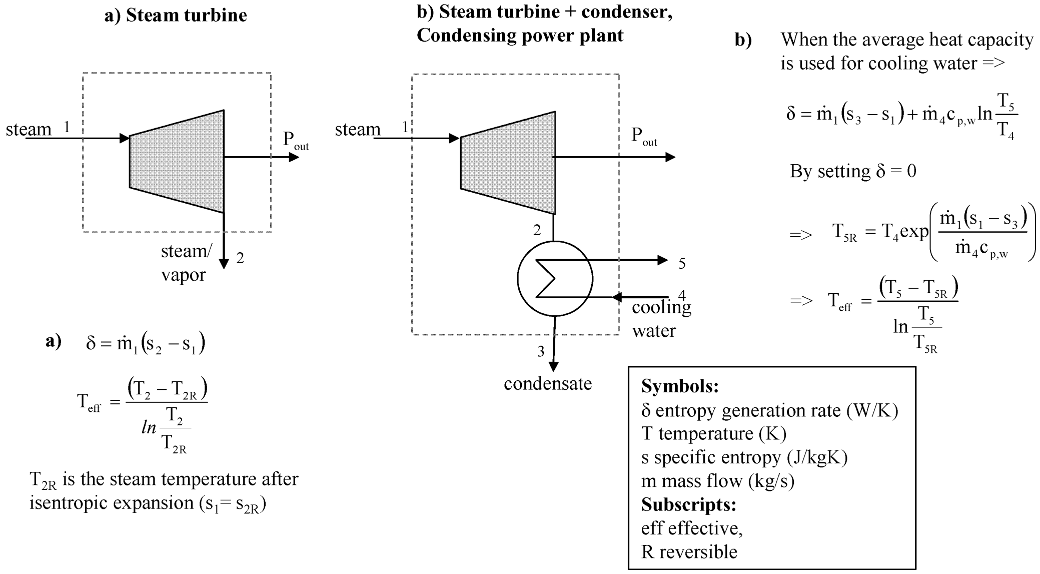


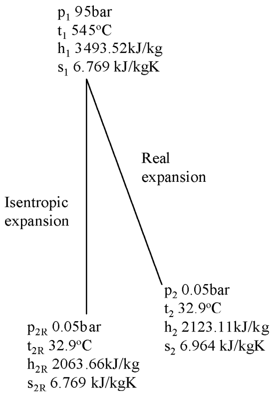
Figure 1. Calculation of power losses for systems studied in this paper

3 Results and discussion

Figure 2 shows an example of the calculation of the power loss for a steam expansion in a condensing and a backpressure turbine. It is trivial that the power loss for a steam expansion in a turbine must be the enthalpy difference h_2–h_{2R} which is 59.45kJ/kg and 87.94kJ/kg for a condensing and a backpressure turbine in the example case, respectively. If the real environmental temperature 20°C is used, the power/exergy loss (see definitions in the Introduction) always becomes 56.95kJ/kg which is not the same as the difference h_2 –h_{2R}. However, the turbine example shows that the Gouy-Stodola law gives the correct power loss when the entropy generation rate is multiplied with the effective temperature defined using Equation (3). This simple example already reveals that it is not always correct to use the real environmental temperature in the Gouy-Stodola law. Example calculations in Figure 3 discusses in more detail when it is correct to use the Gouy-Stodola law for steam turbine calculations.

Figure 3 shows two steam turbine + condenser systems. In a real expansion, the turbine and the condenser generate entropy. In an isentropic expansion, only the condenser generates entropy but steam expansion in a turbine is isentropic. The most important observation in Figure 3 is that the sum of P_{out} + P_{loss} (real power production+ power loss) becomes the same for both expansion cases when effective temperatures are used. The sum of P_{out} + P_{loss} gives the maximum power production of the system when no entropy generation occurs (i.e. a reversible system). As Figure 3 shows the entropy generation rate reduces in isentropic expansion which leads to lower power loss (improvement potential of the system) and greater power production. In the case of isentropic expansion, power loss can be only reduced in a heat exchanger and the improvement potential is 615kW.

Condensing turbine



$$\frac{P_{loss}}{\dot{m}_{steam}} = \frac{P_{max}-P_{real}}{\dot{m}_{steam}} = (h_1-h_{2R})-(h_1-h_2) = (h_2-h_{2R}) = 2123.11-2063.66 = 59.45\text{kJ/kg}$$

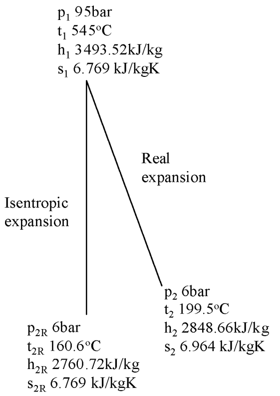
$$T_{eff} = 32.9+273.15 = 306\text{K} = 32.9^\circ\text{C}$$

$$\frac{P_{loss}}{\dot{m}_{steam}} = T_{eff}\delta = T_{eff}(s_2-s_{2R}) = 306\cdot(6.964-6.769) = 59.45\text{kJ/kg}$$

$$T_o = 293.15\text{K} = 20^\circ\text{C}$$

$$\frac{E_{loss}}{\dot{m}_{steam}} = T_o\delta = T_o(s_2-s_{2R}) = 293.15\cdot(6.964-6.769) = 56.95\text{kJ/kg}$$

Backpressure turbine



$$\frac{P_{loss}}{\dot{m}_{steam}} = \frac{P_{max}-P_{real}}{\dot{m}_{steam}} = (h_1-h_{2R})-(h_1-h_2) = (h_2-h_{2R}) = 2848.66-2760.72 = 87.94\text{kJ/k}$$

$$T_{eff} = \frac{T_2-T_{2R}}{\ln\frac{T_2}{T_{2R}}} = \frac{199.5+273.15-160.6-273.15}{\ln\frac{199.5+273.15}{160.6+273.15}} = 452.9\text{K} = 179.8^\circ\text{C}$$

$$\frac{P_{loss}}{\dot{m}_{steam}} = T_{eff}\delta = T_{eff}(s_2-s_{2R}) = 452.9\cdot(6.964-6.769) = 87.98\text{kJ/kg}$$

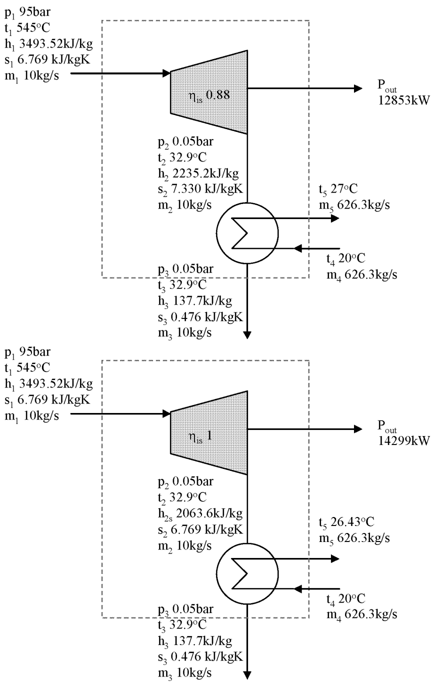
$$T_o = 293.15\text{K} = 20^\circ\text{C}$$

$$\frac{E_{loss}}{\dot{m}_{steam}} = T_o\delta = T_o(s_2-s_{2R}) = 293.15\cdot(6.964-6.769) = 56.95\text{kJ/kg}$$

Figure 2. Example of the calculation of the power loss for a steam expansion in a condensing and a backpressure turbine.

On the basis of Figure 3, it is obvious that the P_{loss} reveals the real improvement potential of the system and the sum of P_{out} + P_{loss} must always be the same for the system. However, this is not valid if the real environmental temperature (20°C in Figure 3) is used instead of the effective temperature. For example, if the real environmental temperature was used In Figure 3, sums of P_{out} + P_{loss} would be 15133kW and 14901kW for real and isentropic expansions, respectively.

The theoretical maximum power production is achieved in all cases when the system only exchanges heat at the environmental temperature. This can be calculated using the classic exergy equation as the example calculation in Figure 3 shows (point a below turbines). Example calculation (point b below turbines) in Figure 3 also shows that it is correct to use the real environmental temperature in the Gouy-Stodola law if the system only exchanges heat with the environment at this temperature (i.e. $P_{max} = P_{out} + P_{loss}$). Because several processes may change heat at much higher or lower temperatures than the real environmental temperature, the use of the environmental temperature in the Gouy-Stodola law may cause a remarkable error for the determination of the power loss. In the cases of this study, the error already becomes considerable for a backpressure turbine (see Fig. 2).



Real expansion

$$\delta = \dot{m}_1 (s_3 - s_1) + \dot{m}_4 c_p \, ln \frac{t_5 + 273.1}{t_4 + 273.15} = 7.777 \frac{kW}{K}$$

$$t_{5R} = (t_4 + 273.15) exp\left(\frac{\dot{m}_1 (s_1 - s_3)}{\dot{m}_4 c_{pv}} \right) - 273.15 = 26.22^\circ C$$

$$T_{eff} = \frac{t_5 - t_{5R}}{ln\left(\frac{t_5 + 273.15}{t_{5R} + 273.15} \right)} = 299.761K$$

$$P_{loss} = T_{eff} \delta = 2331kW$$

$$P_{max} = P_{out} + P_{loss} = 14914kW$$

Isentropic expansion

$$\delta = \dot{m}_1 (s_3 - s_1) + \dot{m}_4 c_p \, ln \frac{t_5 + 273.1}{t_4 + 273.15} = 2.055 \frac{kW}{K}$$

$$t_{5R} = (t_4 + 273.15) exp\left(\frac{\dot{m}_1 (s_1 - s_3)}{\dot{m}_4 c_{pv}} \right) - 273.15 = 26.22^\circ C$$

$$T_{eff} = \frac{t_5 - t_{5R}}{ln\left(\frac{t_5 + 273.15}{t_{5R} + 273.15} \right)} = 299.47K$$

$$P_{loss} = T_{eff} \delta = 615kW$$

$$P_{max} = P_{out} + P_{loss} = 14914kW$$

a) If the system only changes heat at the environmental temperature t_o (=20°C) and steam expansion is isentropic, no entropy generation occurs and the P_{max} becomes:

$$P_{max} = P_{out} = \dot{m}_1 \left[h_1 (95bar, 545^\circ C) - h_{2s} (0.02338bar, 20^\circ C) \right] = 10 \cdot (3493 - 1981) = 15121kW$$

The same result is also obtained using the traditional exergy equation:

$$P_{max} = \dot{m}_1 (e_1 - e_3) = \dot{m}_1 \left[h_1 - h_3' - T_o (s_1 - s_3') \right] = 10 \cdot \left[3493 - 83.8 - 293.15 \cdot (6.769 - 0.269) \right] = 15121kW$$

where s_3' and h_3' are values of the saturated condensate at the temperature of 20°C and pressure of 0.02338bar.

b) If the system only changes heat at the environmental temperature t_o (=20°C) but the turbine generates entropy ($\eta_{is} = 0.88$) then P_{out}, entropy generation rate δ and P_{max} become:

$$P_{out} = \dot{m}_1 \left[h_1 (95bar, 545^\circ C) - h_{2s} (0.02338bar, 20^\circ C) \right] = 10 \cdot (3493 - 2163) = 13307W$$

$$\delta = \dot{m}_1 (s_2 - s_1) = 10 \cdot (7.388 - 6.768) = 6.19kW / K \qquad T_{eff} = T_o = 293.15K \qquad P_{max} = P_{out} + T_o \delta = 13370 + 293.15 \cdot 6.19 = 15121kW$$

Figure 3. Example of the calculation of the power loss for a steam turbine + condenser system

4 Conclusions

Turbine example calculations (Fig. 3) show that it is correct to use the real environmental temperature in the Gouy-Stodola law if the system exchanges heat with the environment only at this temperature. The classic concept of exergy is based on this assumption. However, most industrial processes operate at higher or lower temperatures than the real environmental temperature. In this paper, the maximum power production is achieved when the system is reversible but it does not have to change heat at the real environmental temperature. In these cases, example calculations show that the sum of the power loss and real power production does not give the correct maximum power production for a reversible system if the real environmental temperature is used in the Gouy-Stodola law (Fig. 2 and 3). Especially in the case of CHP plant, errors become remarkable, if the real environmental temperature is used. The paper also shows through turbine examples that the correct power loss can be calculated if the effective temperature defined using Equation (3) is used instead of the real environmental temperature.

5 References

Aljundi H., I., 2009, Energy and exergy analysis of a steam power plant in Jordan. Applied Thermal Engineering, 29 (2009) 324-328.

Bejan A., 1996, Entropy generation minimization. CRCPres, BocaRaton, New York, London, Tokoy.

Holmberg H., Ahtila P, 2008, Evaluation of energy efficiency in direct steam and air drying systems. In Proceedings on the 11th Conference on Process Integration, modelling and process integration (Pres 2008). 24 - 28 August 2008, Prague - Czech Republic

Jiangfeng Wang, Yiping Dai, Lin Gao, 2008, Exergy analyses and parametric optimizations for different cogeneration power plants in cement industry. Applied Energy, article in press.

Kotas T. J., 1995, The Exergy Method of Thermal Plant Analysis. Malabar, Florida.

Lampinen M., Wiksten R., 2006, Theory of Effective Heat-absorbing and Heat Emitting Temperatures in Entropy and Exergy analysis with Applications to Flow Systems and Combustion Process. Journal of Non-Equilibrium Thermodynamics, Vol. 31 257-291.

Lampinen M.J., Heikkinen M.A., 1995, Exergy Analysis for stationary flow systems with several heat exchange temperatures. International Journal of enrgy Research Vol. 19, 407-418.

Struchtruo H., Rosen M., 2002, How much work is lost in an irreversible turbine. Exergy, an international journal 2 (2002) 152-158.

Szargut J., 2005, The Exegy Method: Technical and Ecological Applications. WITPress, UK, USA.

Szargut J., Morris D.R., Steward F.R., 1988, Exery analysis of thermal chemical and metallurgical processes. Hemisphere Publishing Corporation, New York, Washington, Philadelphia, London.