Jurnal Teknologi

MATLAB as a Tool for the Teaching of Rankine Cycle with Simulation of a Simple Steam Power Plant

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Graphical abstract
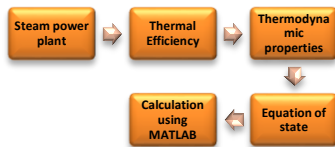
Abstract

Rankine cycle is one example of vapor power cycles. One important application is in steam power plants. Properties of the important points in the cycle can be found from steam tables. However, reading values from a steam table is rather inconvenient particularly when there are many values to be read such in a simulation. Interpolation must often be done since the table only provides values of properties at determined points. Using equations of states for steam is very convenient since values can be computed quickly. Unfortunately, equations of states for steam are very complicated. A program written in MATLAB to assist the teaching of Rankine cycle using steam has been developed. MATLAB is used since it is widely available. Using this program, a lecturer can easily modify a problem and get the answer quickly. Students can also benefit from the program where they can solve problems and compare the results that they will get manually.

Keywords: Rankine cycle, steam power plant, equation of states, MATLAB

Abstrak

Kitar Rankine adalah salah satu contoh kitar kuasa wap. Satu penggunaan penting adalah pada loji kuasa stim. Sifat-sifat daripada titik-titik penting pada kitar dapat didapatkan dari jadual stim. Namun pembacaan nilai-nilai dari jadual stim agak susah terutamanya jika banyak nilai yang harus dibaca sperti pada sebuah simulasi. Penentudalaman sering harus dibuat kerana jadual hanya memberikan nilai-nilai sifat pada titik-titik tertentu saja. Pemakaian persamaan keadaan untuk stim sangat mudah kerana nilai-nilai dapat dikira dengan pantas. Malangnya, persamaan keadaan untuk stim sangat rumit. Satu program yang ditulis dalam MATLAB untuk membantu pengajaran kitar Rankine yang menggunakan stim telah dibuat. Dengan menggunakan program ini, pensyarah boleh mengubahsuai satu masalah dan mendapatkan jawaban dengan pantas. Pelajar juga boleh mendapat manfaat dari program dimana mereka boleh menyelesaikan masalah dan membandingkan hasil-hasil dengan yang mereka dapat secara manual.

Kata kunci: Kitar Rankine, loji kuasa stim, persamaan keadaan, MATLAB

1.0 INTRODUCTION

Thermodynamics is one of core subjects taught at the School of Mechatronic Engineering, Universiti Malaysia Perlis (UniMAP). One of the topics taught in thermodynamics is Rankine cycle. One important application of the cycle is in steam power plants. The performance of a steam power plant is measured by its thermal efficiency, which needs values at important points of the cycle. A simple steam power plant is shown in Figure 1.

The T-s diagram of the cycle is shown in Figure 2. Processes in the Rankine cycle can be briefly explained as follow. For more detailed, see [1-2] or any other engineering thermodynamics textbooks. Water enters the pump as saturated liquid at t1 and pumped isentropically to t1' at p2. The water is then preheated to t2 before entering the boiler where it is converted into superheated steam at p4 and t4. For an ideal cycle, we assume there is no pressure loss in the heat exchanger (boiler and condenser) so p2=p3=p4 and p1 = p6. The steam enters the turbine which develops power and then flows to the condenser where the pressure and the temperature decrease. In Figure 2, the water which exits from the turbine is a mixture of saturated liquid and vapor. However, it can be saturated vapor or superheated steam, depends on the condenser's pressure. Ideally, the steam is expanded isentropically (shown as 4–5s). In practice, there is loss so the actual process is shown as 4–5.
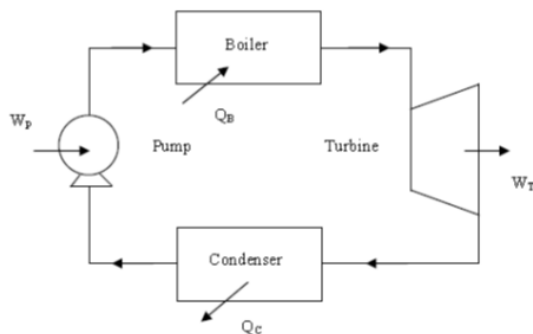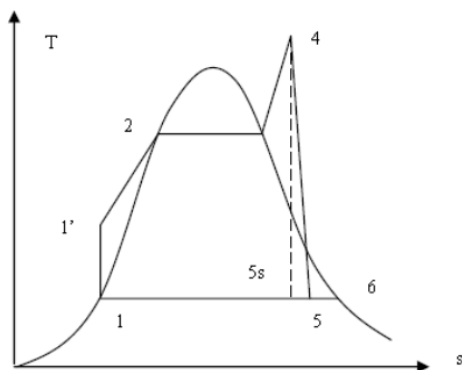

Figure 1 A simple steam power plant

Figure 2 T-s diagram for the cycle

2.0 THERMAL EFICIENCY OF THE CYCLE

For the calculation of the thermal efficiency, we asume that the mass flow rate of the steam is 1 kg/s. Also we assume that the pump and the turbine are adiabatic with adiabatic efficiencies of η_P and η_T, respectively. Thermal efficiency of the cycle can be found from

$$\eta_{th} = \frac{W_N}{Q_B} = \frac{W_T - W_P}{Q_B} \tag{1}$$

where

W_N = net power, kW,
W_T = power developed by the turbine, kW
W_P = power needed by the pump, kW
Q_B = heat absorbed by the boiler, kJ/s or kW.

Power developed by the turbine is given by $W_T = \dot{m}(h_4 - h_5)$ where $W_T = \dot{m}(h_4 - h_{5s})/\eta_T$. Power needed by the pump is given by $W_P = \dot{m}(h_1' - h_1)$ but this can be approximated as $\dot{m}v_1'(p_2 - p_1)$ since the temperature increase in the pump is quite small. Heat absorbed by the boiler is given by $Q_B = \dot{m}(h_4 - h_2)$. All formulas mentioned here are given in most thermodynamics textbooks; see [1-2], for example.

3.0 EQUATIONS OF STATES FOR STEAM

Values of properties needed for the formulas in the previous section can be found from steam tables which are given in most thermodynamics textbooks. More complete tables can be seen in [3–5].

However, reading values from a steam table is rather inconvenient particularly when there are many values to be read such in a simulation. Interpolation must often be done since the table only provides values of properties at determined points. Also, properties in steam table are given as a function of pressure or temperature (saturated liquid and vapor), or as a function of temperature and pressure (superheat steam or subcooled water). As example, suppose we want to find the temperature of superheat steam if the pressure and enthalpy is given. We must interpolate the superheat steam to find the temperature and often we must do the double interpolation.

Using equations of states for steam is very convenient since values can be computed quickly. Unfortunately, equations of states for steam are very complicated [5-8]. Simplified formulas at for water properties at 0.1 MPa are given in [9]. Calculators to find the steam properties are avalaible in the internet but the user must calculate formulas separately. Here, a program written in MATLAB to assist the teaching of Rankine cycle using steam has been developed. MATLAB is chosen since it is widely available and writing a program with it is not difficult; see [10-11], for example. The formulas for equations of states for steam for this program are taken from [5] and called IAPWS Industrial Formulation 1997 or IAPWS-IF97 for

short. The formulas are also available in the website: www.iapws.org. The formulas in IAPWS-IF97 are divided into five regions which cover the following range of validity:

$$273.15 \text{ K} \leq T \leq 1073.15 \text{ K}, \; 0 < p \leq 100 \text{ MPa}$$
$$1073.15 \text{ K} < T \leq 2273.15 \text{ K}, \; 0 < p \leq 50 \text{ MPa}$$

However, this paper only considers three regions which are important for the teaching of Rankine cycle.

First region covers the liquid state of water; properties for first region can be derived from (2):

$$\frac{g_1(p,T)}{RT} = \gamma(\pi, \tau) = \sum_{i=1}^{34} n_i (7.1 - \pi)^{I_i} (\tau - 1.22)^{J_i} \quad (2)$$

Here, $\pi = p/p^*$, $\tau = T^*/T$ where $p^* = 16.53$ MPa, $T^* = 1386$ K and $R = 0.461526$ kJ/kg.K. γ is dimensionless Gibbs free energy function. Coefficients of n_i, I_i and J_i are given in [5]. Thermodynamic properties are given in terms of γ as follow:

$$v(\pi, \tau)\frac{p}{RT} = \pi\gamma_\pi; \frac{h(\pi,\tau)}{RT} = \tau\gamma_\tau; \frac{s(\pi,\tau)}{R} = \tau\gamma_\tau - \gamma \quad (3)$$

Here, $\gamma_\pi = (\partial\gamma/\partial\pi)_\tau$ and $\gamma_\tau = (\partial\gamma/\partial\tau)_\pi$.

Second region covers superheat steam; properties for second region can be derived from (4):

$$\frac{g_1(p,T)}{RT} = \gamma(\pi, \tau) = \gamma^0(\pi, \tau) + \gamma^r(\pi, \tau) \quad (4)$$

Here, γ^0 is the ideal-gas part and γ^r is the residual part. The dimensionless ideal-gas part γ^0 and residual part γ^r are given by(5) and (6), respectively:

$$\gamma^0(\pi, \tau) = \ln(\pi) + \sum_{i=1}^{9} n_i \tau^{J_i^0} \quad (5)$$
$$\gamma^r(\pi, \tau) = \sum_{i=1}^{43} n_i \pi^{I_i} (\tau - 0.5)^{J_i} \quad (6)$$

Coefficients for both equations are given in [5]. Here, $\pi = p/p^*$, $\tau = T^*/T$ where $p^* = 1$ MPa and $T^* = 1$ K. Thermodynamic properties are given in terms of γ^0 and γ^r as follow:

$$v(\pi, \tau)\frac{p}{RT} = \pi(\gamma_\pi^0 + \gamma_\pi^r) \quad (7)$$
$$\frac{h(\pi,\tau)}{RT} = \tau(\gamma_\tau^0 + \gamma_\tau^r) \quad (8)$$
$$\frac{s(\pi,\tau)}{R} = \tau(\gamma_\tau^0 + \gamma_\tau^r) - (\gamma^0 + \gamma^r) \quad (9)$$

Third region covers saturated steam that is liquid and vapor. Properties for third region can be derived from (2) for saturated liquid and from (4) for saturated vapor. Saturation pressure and temperature are computed from (10) and (11):

$$\frac{p_S}{p^*} = \left[\frac{2C}{-B + \sqrt{B^2 - 4AC}}\right]^4 \quad (10)$$
$$\frac{T_S}{T^*} = \frac{n_{10} + D - \sqrt{(n_{10}+D)^2 - 4(n_9 + D)}}{2} \quad (11)$$

Coefficients A to G are given as follow:

$$D = \frac{2G}{-F - \sqrt{F^2 - 4EG}}$$

$A = v^2 + n_1 v + n_2$; $B = n_3 v^2 + n_4 v + n_5$; $C = n_6 v^2 + n_7 v + n_8$;

$E = \beta^2 + n_3\beta + n_6$; $B = n_1 \beta^2 + n_4\beta + n_7$; $C = n_2\beta^2 + n_5\beta + n_8$.

x v and β are defined as

$$v = \frac{T_S}{T^*} + \frac{n_9}{(T_S/T^*) - n_{10}}; \quad \beta = \left(\frac{p_S}{p^*}\right)^{0.25}$$

Coefficients of n_1 to n_{10} are given in [5].

4.0 SIMULATION OF THE RANKINE CYCLE

Simulation of the Rankine cycle is done by taking the following values. Efficiencies of the turbine and pump are taken to be 0.87 and 0.80, respectively. Condenser's temperatures, boiler's pressure and superheat temperatures are varied. The results are shown in Tables 1 to 4.

Table 1 Thermal efficiency at (40°C, 10 bar), t_4 from 300 to 500°C

	$t_1 = 40°C$ ($p_1 = 0.0738$		$p_2 = 10$ bar ($t_2 = 179.89°C$)		
	t_4, °C				
	300	350	400	450	500
W_P	1.2598	1.2598	1.2598	1.2598	1.2598
W_T	724.1176	768.2173	815.9603	867.1860	921.7111
Q_B	2289.0	2.3955	2.5017	2.6085	2.7163
η_{th}	0.3158	0.3202	0.3257	0.3320	0.3389

Table 2 Thermal efficiency at (40°C, 15 bar), t_4 from 300 to 500°C

	$t_1 = 40°C$ ($p_1 = 0.0738$		$p_2 = 15$ bar ($t_2 = 198.30°$)		
	t_4, °C				
	300	350	400	450	500
W_P	1.8898	1.8898	1.8898	1.8898	1.8898
W_T	768.2290	813.6913	862.3830	914.3180	969.3990
Q_B	2.1935	2.3033	2.4116	2.5199	2.6288
η_{th}	0.3494	0.3524	0.3568	0.3621	0.3680

Table 3 Thermal efficiency at (45°C, 10 bar), t_4 from 300 to 490°C

	$t_1 = 45°C$ ($p_1 = 0.0959$		$p_2 = 10$ bar ($t_2 = 179.89°C$)		
	t_4, °C				
	300	350	400	450	490
W_P	1.2624	1.2624	1.2624	1.2624	1.2624
W_T	695.7565	768.2173	786.1113	836.6712	879.5314
Q_B	2289.0	2.3955	2.5017	2.6085	2.7163
η_{th}	0.3034	0.3080	0.3137	0.3203	0.3259

Table 4 Thermal efficiency at (45°C, 15 bar), t_4 from 300 to 500°C

	$t_1 = 45°C$ ($p_1 = 0.0959$		$p_2 = 15$ bar ($t_2 = 198.30°C$)		
	t_4, °C				
	300	350	400	450	500
W_P	1.8936	1.8936	1.8936	1.8936	1.8936
W_T	740.7590	785.4225	833.3867	884.6467	939.0941
Q_B	2.1935	2.3033	2.4116	2.5199	2.6288
η_{th}	0.3368	0.3402	0.3448	0.3503	0.3565

5.0 CONCLUSION

Various programs to compute property values of water at three regions have been developed using MATLAB. Those programs are then used by another program that can simulate a Rankine cycle. This program should be useful for lecturers for the teaching of Rankine cycle as a part of thermodynamics subject. Students can also benefit from the program as well.

Acknowledgement

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